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FINAL REPORT

VOLUME TWO

of

Contract NAS5-21876

INVESTIGATIONS USING DATA IN ALABAMA FROM ERTS-A

Principal Investigator

DR. HAROLD R. HENRY

Submitted to

Goddard Space Flight Center
National Aeronautics and Space Administration
Greenbelt, Maryland

August, 1974

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GSFC Proposal No. 271

Principal Investigator

DR. HAROLD R. HENRY
GSFC ID UN604

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Submitted by

Bureau of Engineering Research
The University of Alabama
University, Alabama

August, 1974

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THE FEASIBILITY OF USING REMOTELY SENSED DATA FROM ERTS-I FOR LAND-USE INVENTORY, MANAGEMENT AND PLANNING

Richard P. Wilms

SECTION SIX

of

VOLUME TWO

INVESTIGATIONS USING DATA IN

ALABAMA FROM ERTS-A

THE FEASIBILITY OF USING REMOTELY SENSED DATA FROM ERTS-I FOR LAND-USE INVENTORY, MANAGEMENT AND PLANNING

A SPECIAL REPORT

by

Richard Paul Wilms

Contract NAS5-21876
GSFC Proposal No. 271
"Investigations Using Data in
Alabama from ERTS-A"

Principal Investigator
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LIST OF ACRONYMS

ADO - Alabama Development Office

DCP - Data Collection Platform

DCS - Data Collection System

ERTS - Earth Resources Technology Satellite

MIADS - Multi-Informational and Display System

MSS - Multispectral Scanner

NASA - National Aeronautics and Space Administration

NDPF - NASA Data Processing Facility

NMAS - National Map Accuracy Standards

NTTF - Network Test and Training Facility

RBV - Return Beam Vidicon

SCS - Soil Conservation Service

USGS - United States Geological Survey

UTM - Universal Transverse Mercator (map coordinates)

WBVTR - Wide Band Video Tape Recorder

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This report was submitted as a thesis in partial fulfillment of the requirements for the degree of Master of Science in the Department of Civil and Mineral Engineering in the Graduate School of The University of Alabama.

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INTRODUCTION

1.1 The ERTS-I Satellite

High above the earth's surface, at an altitude of 914 kilometers, the NASA Earth Resources Technology Satellite (ERTS-I) is surveying our planet enabling us to learn more about our resources and thus manage them better through remote sensing. Launched by NASA on July 23, 1972, ERTS-I is the first spacecraft designed specifically for monitoring natural resources, environmental quality, and the activities of man.

From its celestial vantage point, the 891 kilogram (1964 pounds) moth-shaped satellite orbits the earth in a nearly circular orbit (912 kilometers apogee and 917 kilometers perogee) every 103 minutes, sensing 185-kilometer-wide strips of the earth's surface. More than 6.5 million square kilometers (2.5 million square miles) of the earth's surface are "photographed" by the satellite each day.

In its sun-synchronous orbit, ERTS-I "views" virtually the same slice of the earth every eighteen days at about the same time of day (09:30 local sun time for Alabama). The orbit inclination allows the orbit plane to advance one degree per day so that the orbit plane relative to the sun is maintained. The lighting conditions are thus nearly the same for all images of the same area, considering, of course weather and seasonal changes.[1] Three 115-mile strips of North America are mapped each day along with another eleven such strips in selected

areas of the rest of the world. ERTS-I coverage of the continental United States is displayed in Figure 1. Similar strips on the next day are contiguous to the strips taken on the previous day, thus providing systematic, repetitive coverage of the land surface on a global scale, while at the same time maintaining maximum consistency. Figure 2 illustrates the ground coverage pattern.

During its first seven months in orbit, ERTS-I imaged every major land mass at least once and all of North America ten times. It had taken approximately 33,000 separate scenes as of March 9, 1973, from which the NASA Data Processing Facility (NDPF) at the Goddard Space Flight Center Produced over 1,440,659 images.

Each ERTS-I scene, representing approximately 34,251 square kilometers (13,225 square miles), approximates a true cartographic map[2] meeting or, in some instances, exceeding National Map Accuracy Standards (NMAS)*. This accuracy, along with ERTS-I's ability to view vast areas of the earth's surface in minutes, has shown the spacecraft to be a very economical instrument for inventorying natural resources.

ERTS-I derives its capabilities from a pair of imaging systems--the multispectral scanner (MSS) and return beam vidicon (RBV) camera. Both sensor systems are equipped to "photograph" the earth in three spectral bands (green, red, and infrared). The MSS system also possesses a fourth band further into the infrared portion of the spectrum. A more detailed discussion of the sensors aboard ERTS-I will be given in a subsequent portion of this chapter.

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*At 1:1,000,000 scale, a system-corrected (bulk) MSS image should meet NMAS, but at 1:500,000, the error may be about twice the tolerance of NMAS.

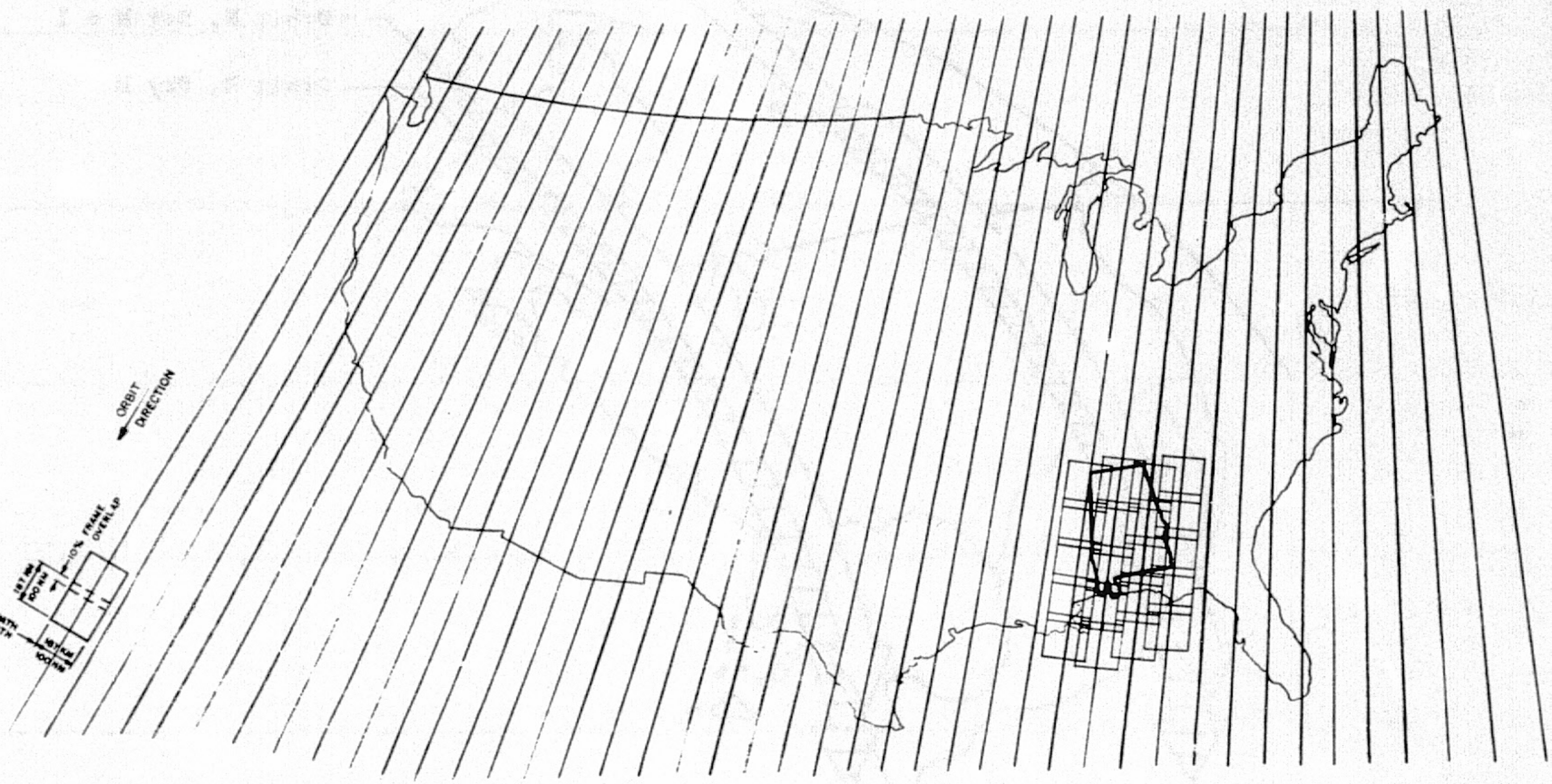

Figure 1. ERTS-I Coverage of the United States.

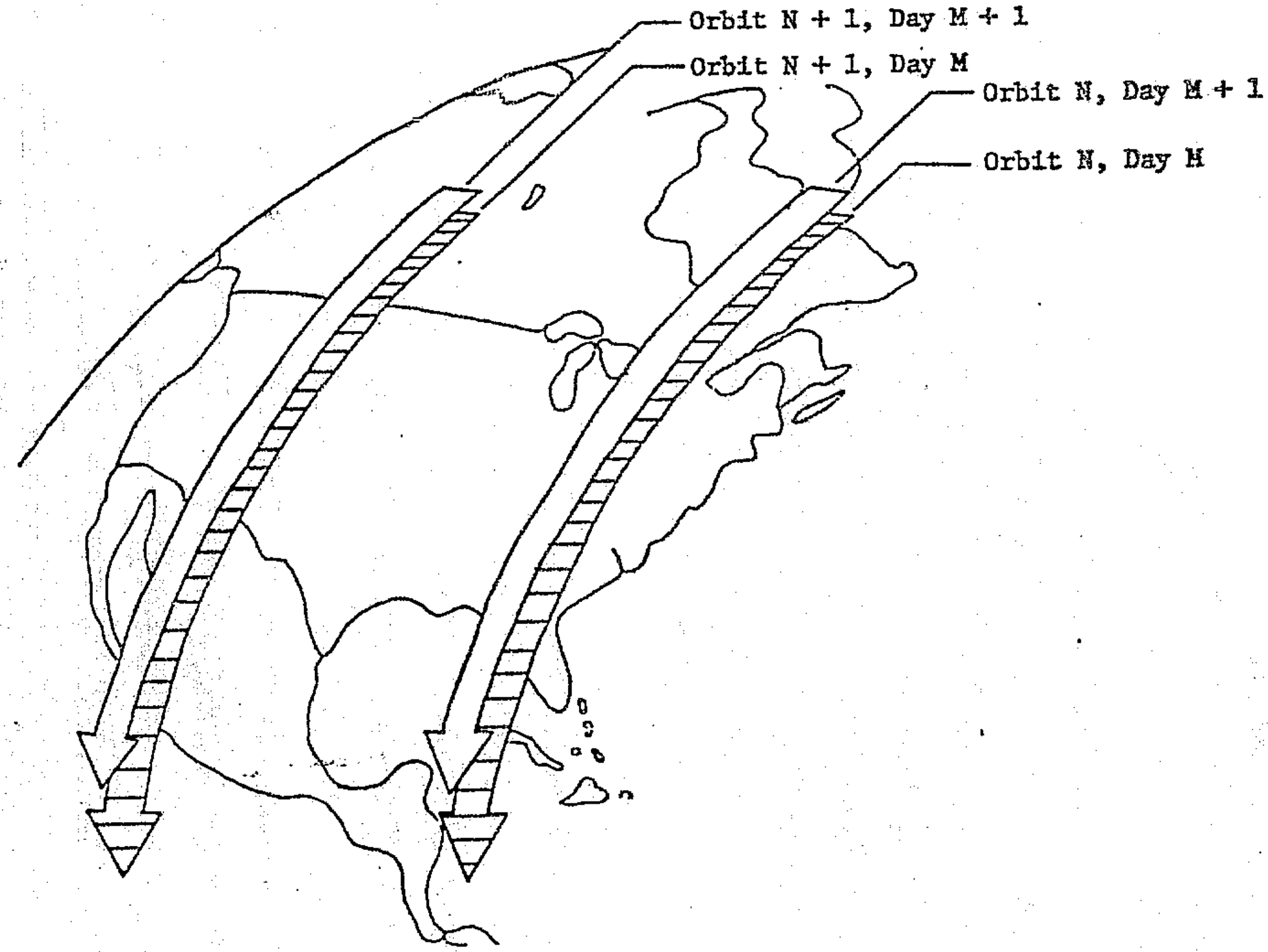

Figure 2. ERTS-I Ground Coverage Pattern.

ERTS-I is also equipped with a Data Collection System (DCS) which acquires data from ground based sensing platforms distributed over North America. Seven Data Collection Platforms (DCP's), located along the Black Warrior River and in Mobile Bay (Figure 3) monitor water quality parameters (pH, temperature, conductivity, and dissolved oxygen) and telemeter that information to ERTS-I as it passes overhead for ultimate transmission to the NASA/Goddard Space Flight Center, Greenbelt, Maryland. Figure 4 illustrates the ERTS-I satellite.

At the present time, only the MSS sensors are being operated. The RBV system was shut down shortly after launch because of two unexplained anomalies. The first was concerned with one of the two tape recorders aboard which is used to record images when the satellite is not over North America. The second recorder is operating satisfactorily in its place, however. The second anomaly affected the power supply circuitry for the RBV cameras. In the event of the demise of the MSS sensors, however, the RBV system could be activated and used in conjunction with the one remaining video tape recorder.[3]

Information gathered by the MSS system as well as DCS measurements are transmitted to three ground receiving stations in the United States (Goldstone, California; Fairbanks, Alaska; Greenbelt, Maryland) and to a Canadian station in Saskatchewan. There, the ERTS-I signals are recorded on tapes which are then converted into images.

1.2 ERTS-I Sensors

As previously stated, ERTS-I is equipped with two separate remote sensing systems. This duplicity of sensors, first considered by many

Figure 3. Locations of Data Collection Platforms in Alabama.

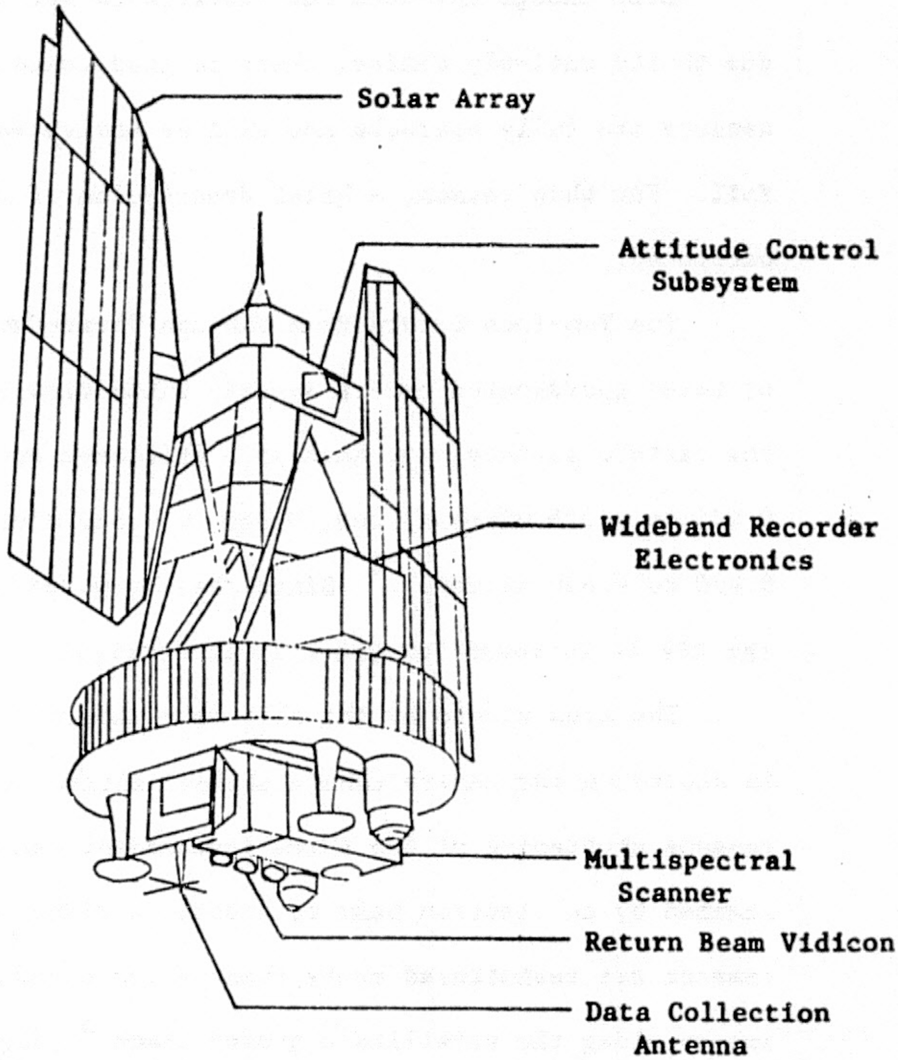

Figure 4. ERTS-I Anatomy.

to be redundant, was demonstrated worthwhile when, after a mysterious power surge swept through the spacecraft shortly after launch, the RBV system had to be shut down.

Even though RBV data was unavailable for use in this investigation, due to its untimely demise, there is good reason to believe that the RBV sensors are fully operable and will be activated should the MSS system fail. For this reason, a brief description of the RBV system is warranted.

The Two-Inch Return Beam Vidicon Three-Camera Subsystem consists of three coordinated camera sensors which view the identical scene on the earth's surface, but each in a different spectral band (blue-green, 0.475 to 0.575 microns; red, 0.580 to 0.680 microns; and infrared, 0.690 to 0.830 microns).[4] Since these cameras receive reflected energy, the RBV is intended for use only in daylight.

The area viewed by the RBV, measuring 185 by 185 kilometers square, is stored on the camera tube's photosensitive surface. After the simultaneous shuttering of the three independent cameras, the image is scanned by an electron beam to produce a video signal output. The RBV cameras are reshuttered every twenty-five seconds to render overlapping images along the satellite's ground track.[5] Figure 5 illustrates the orientation of the three camera heads.

The multispectral scanner, which has absorbed the observational slack left by the shutdown of the RBV system, consists primarily of a line-scanning apparatus using an oscillating mirror to continuously scan the surface normal to the satellite's ground track as shown in Figure 6. A diagrammatic sketch of the scanner, contained in Figure

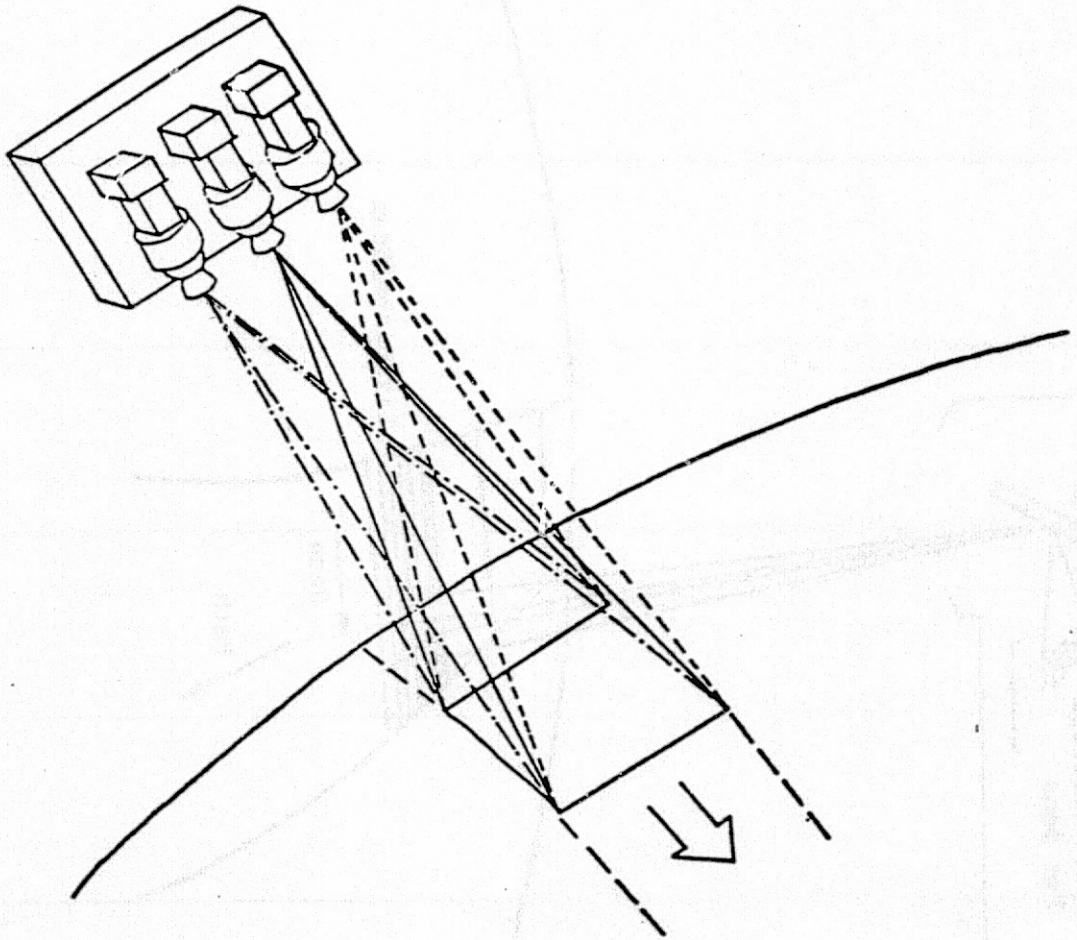

Figure 5. Orientation of the Return Beam Vidicon System.

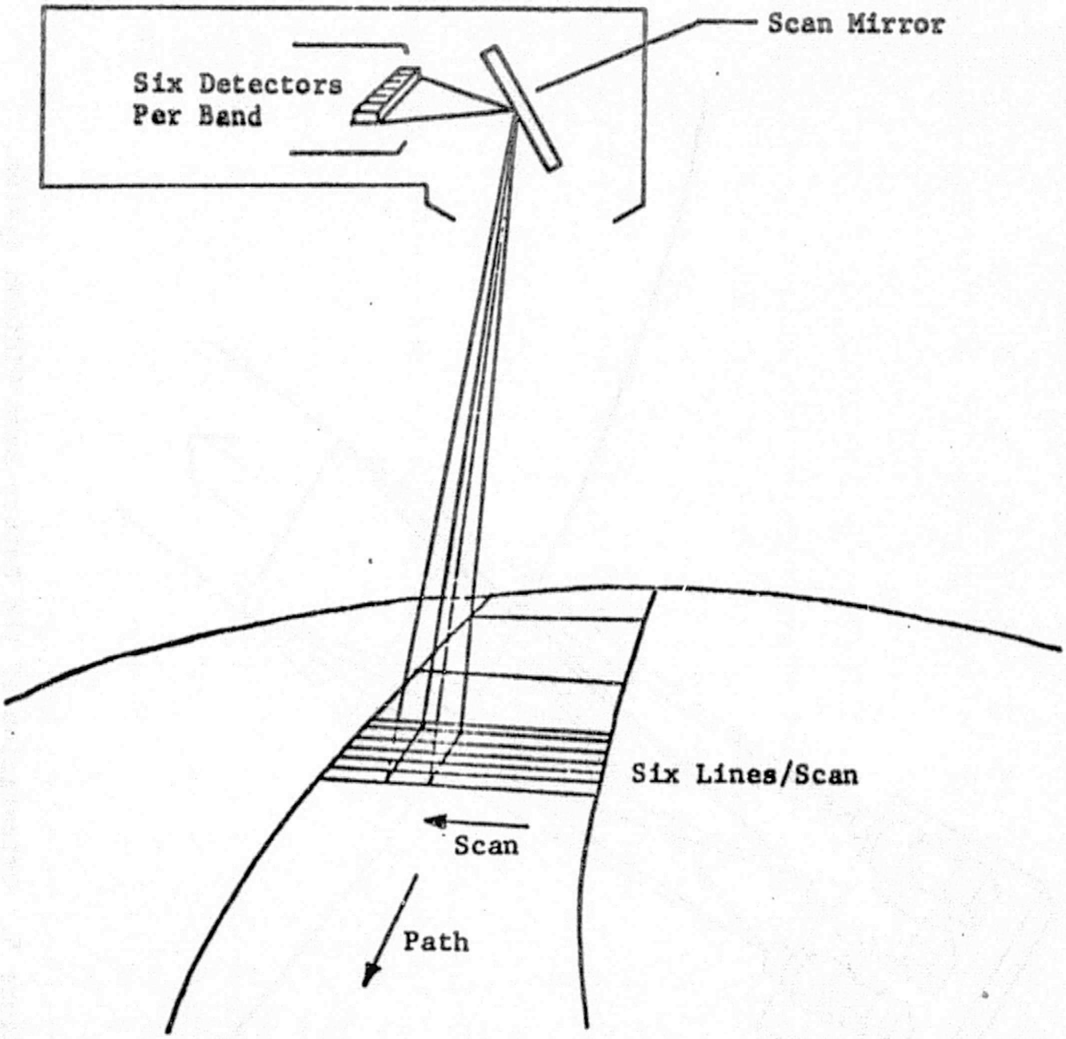

Figure 6. MSS System for Imaging Ground Cover.

7, shows the scanner elements relative to the orbit. Earth is downward and the nominally southbound velocity vector is away from the reader.

The scanner's flat, elliptically-shaped nine by 13 inch mirror is oriented 45 degrees with respect to the telescope axis and nadir line. The mirror rotates $\pm$ 2.9 degrees about the velocity vector thus scanning a line across the 185 kilometer (115 miles) wide swath, sweeping that same line across the telescope focus. The forward movement of ERTS-I is such that during the time required to scan across the 185-kilometer-wide swath, the spacecraft has advanced six fields of view. Therefore, six lines, instead of just one, are imaged in each of four spectral bands during each sweep. By the time the mirror has returned for the next sweep, the satellite has advanced sufficiently (1554 feet) so that the next six lines scanned are contiguous to the previous six.[6]

MSS sensors "catch" varying amounts of reflected and emitted electromagnetic energy from the earth in four spectral bands ranging from 0.5 to 1.1 microns. Figure 8 contrasts the spectral response of the MSS sensors to that of the RBV sensors.

On board the spacecraft, the energy readings are converted into electrical signals in the four bands, digitized, and transmitted back to earth in real time or stored in one of two on-board wide band video tape recorders (WBVTR) for transmission to a ground receiving station at a later time.

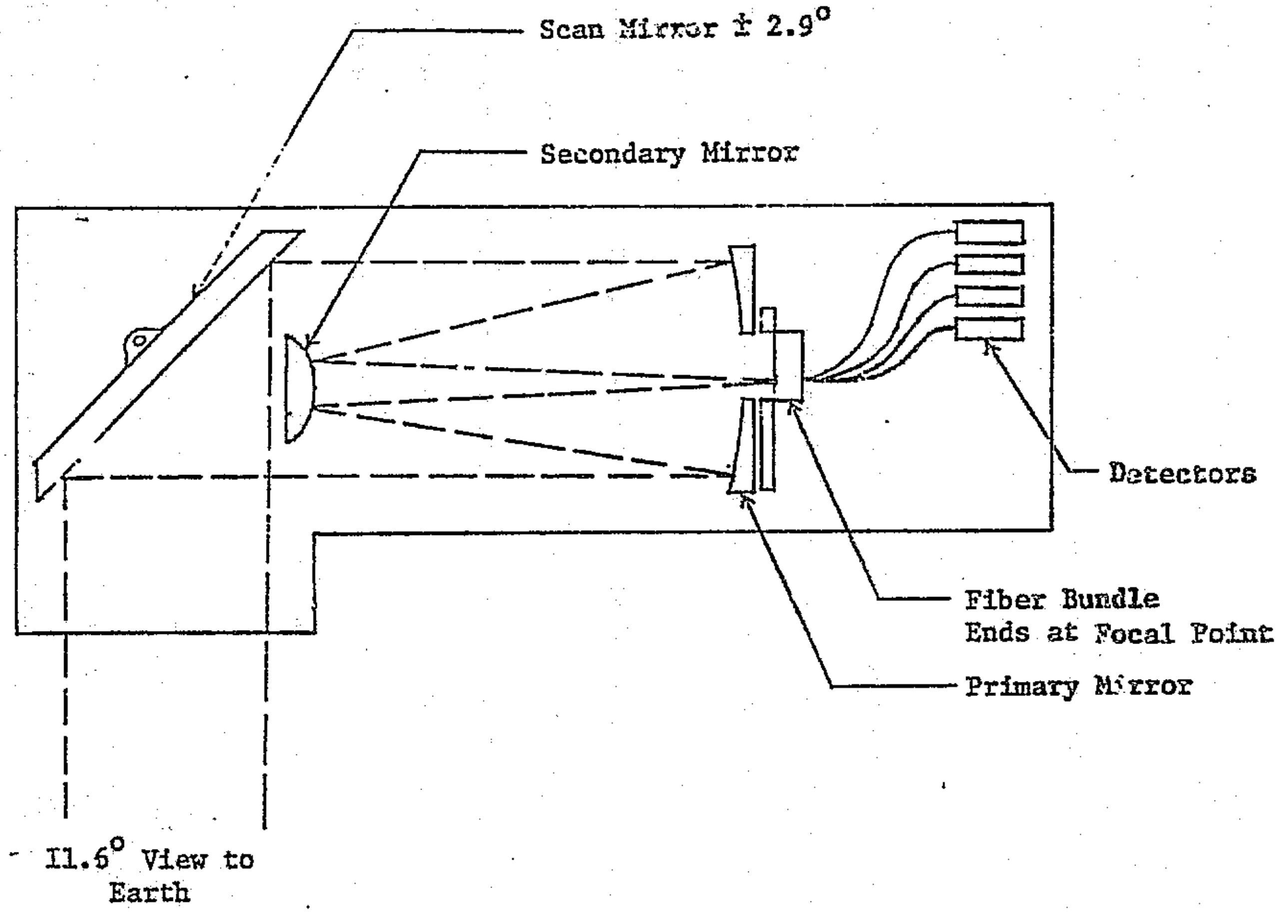

Figure 7. Schematic Drawing of the ERTS-I Multispectral Scanner.
(From Hughes Aircraft Company)

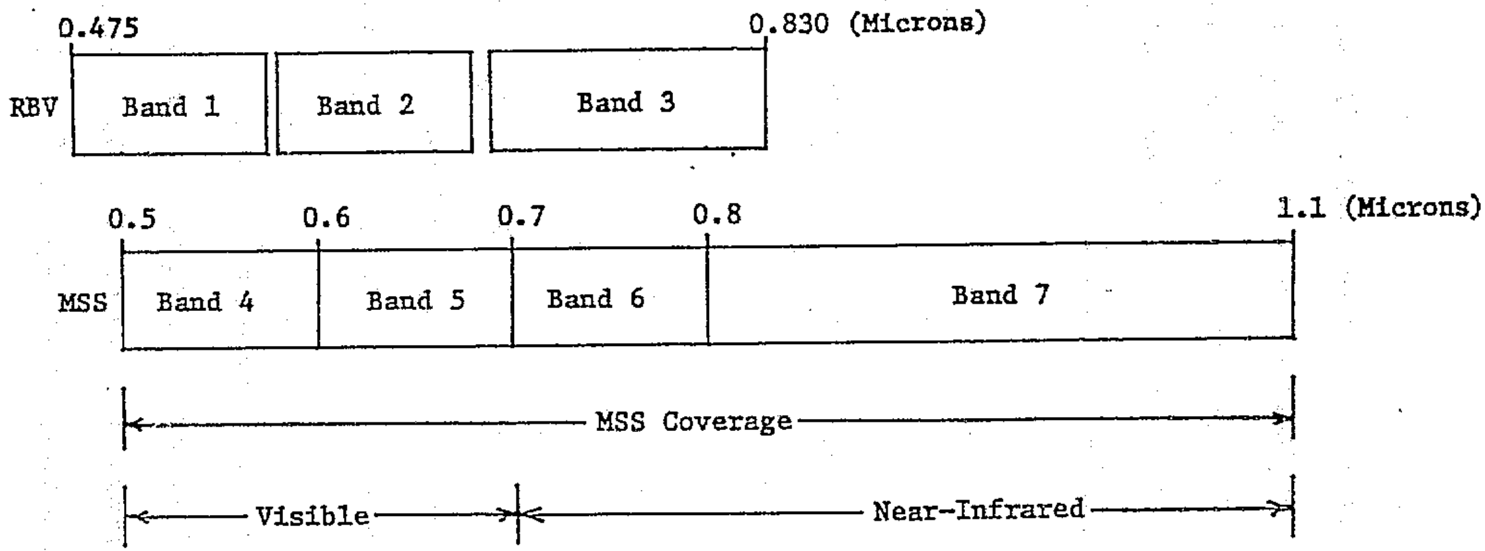

Figure 8. The Portion of the Electromagnetic Spectrum Imaged by ERTS-I Sensors.

1.3 ERTS-I Imagery

The basic product produced by NASA (Goddard Space Flight Center) from ERTS-I data is known as system-corrected (bulk) imagery. It is available in two different formats, as 70 mm transparencies (positive or negative) at a scale of 1:3,369,000 or in a 9.5 by 9.5 inch (240 mm nominal) transparencies and prints (positive or negative) at a scale of 1:1,000,000.

A sample of the MSS bulk image format, including registration marks, tick marks, gray scale, and alphanumeric annotation, is shown in Figure 9. Four registration marks beyond the corners of the image (two are shown) facilitate the alignment of spectral images of the same scene and date but of different spectral bands. Exact alignment of the registration marks of two or more images of the same date and scene will cause the contents of these images to be registered.

Tick marks indicating latitude and longitude at intervals of 30 arc minutes are found just outside the edge of the image. The geographic reference marks are appropriately annotated in degree-minutes and direction.

The alphanumeric annotation shown near the bottom of Figure 9 contains information concerning geographic location and time of exposure of the scene to which it is attached. The following paragraphs explain the alphanumeric annotation of Figure 9.[7]

1) 16OCT72: Day, month, and year of picture exposure.
2) C N31-46/W086-13: Format center; latitude and longitude in degrees and minutes at the center of the MSS image format

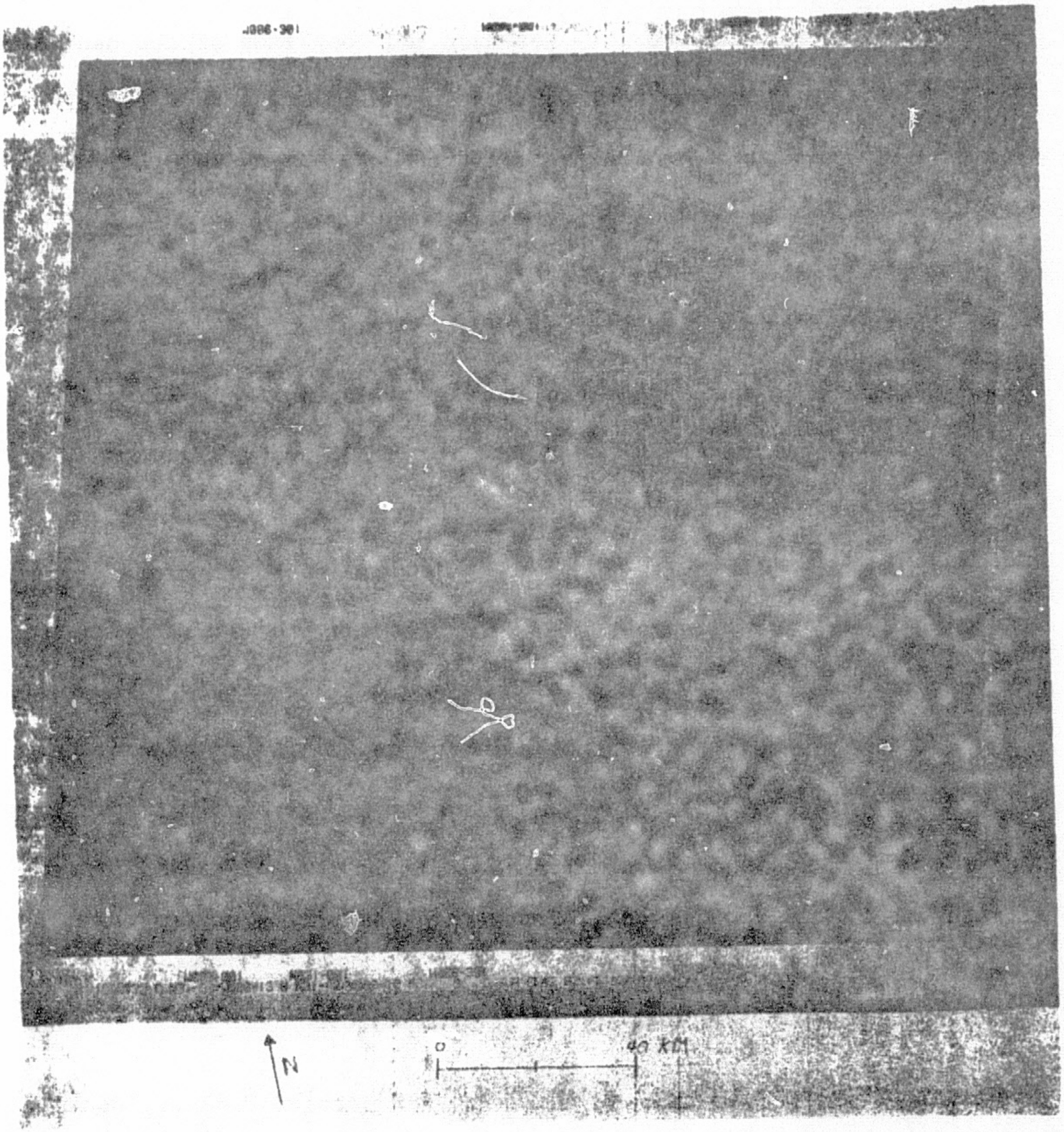

Figure 9. An ERTS-I Scene of the Montgomery Area Illustrating the Alphanumeric Annotation.

(point of intersection of diagonals connecting registration marks).

3) N N31-42/W086-10: Latitude and longitude of the nadir (the intersection with the earth's surface of a line from the satellite perpendicular to the earth ellipsoid) in degrees and minutes.

4) MSS 6: Sensor and NDPF spectral band identification code.

5) D:"D" indicates direct (real time) transmission.

6) SUN EL42 AZ145: The sun elevation angle and sun azimuth angle measured clockwise from true north at the midpoint of MSS frame to the nearest degree.

7) 190-1184-N-1: "190" is the satellite heading to the nearest orbit number: "N" refers to the ground recording station (NTTF): 1 means the image as full size.

8) N-D-2L: "N" indicates normal processing procedures were used: "D" indicates definitive or best fit ephemeris was used: "2" indicates a compressed mode of MSS signal processing prior to transmission from satellite to ground station: "L" refers to low gain.

9) NASA ERTS: Agency and project.

10) E-1085-15501-6: "E" stands for Encoded Project Identifier: "1" refers to ERTS-I: "085" gives the number of days after launch: "15" gives the number of hours at time of exposure: "50" gives minutes at time of exposure: "1" gives tens of seconds at time of exposure (Greenwich mean time): "6" is the NDPF identification code for MSS 6.

Directly beneath the alphanumeric annotation block is exposed a fifteen step gray scale. It has been subjected to the same copying and processing as the image to which it is attached. The gray scale denotes the relationship between a level of gray on the image and the electron beam density used to expose the original image which, in turn, is related initially to the electromagnetic energy incident on the MSS sensor aboard the satellite.

The images can be either black-and-white reproductions of the scene in each of the four spectral bands, or a color composite of any combination of bands, referred to as a "false-color" photograph. Examination of the images contained in Figure 10 (a-d) demonstrates how features on the ground can appear quite different in each spectral band. Forested areas appear dark in MSS bands four and five and relatively light in band seven. Interstate highways which are very prominent on the visible bands four and five disappear on bands six and seven. Likewise, both free-flowing and impounded water appears black on bands six and seven because of the almost total absorption by water of electromagnetic energy in the infrared portion of the spectrum; yet, water is almost impossible to detect using spectral bands four and five. In addition, cities and towns which are visible as pale shades of gray on bands four and five are darker and not as readily apparent on bands six and seven.

Although most of the analysis and interpretation of ERTS-I imagery in this investigation was accomplished using individual black-and-white images in the four spectral bands, a composite image often rendered geographic and interpretive information that otherwise would not have

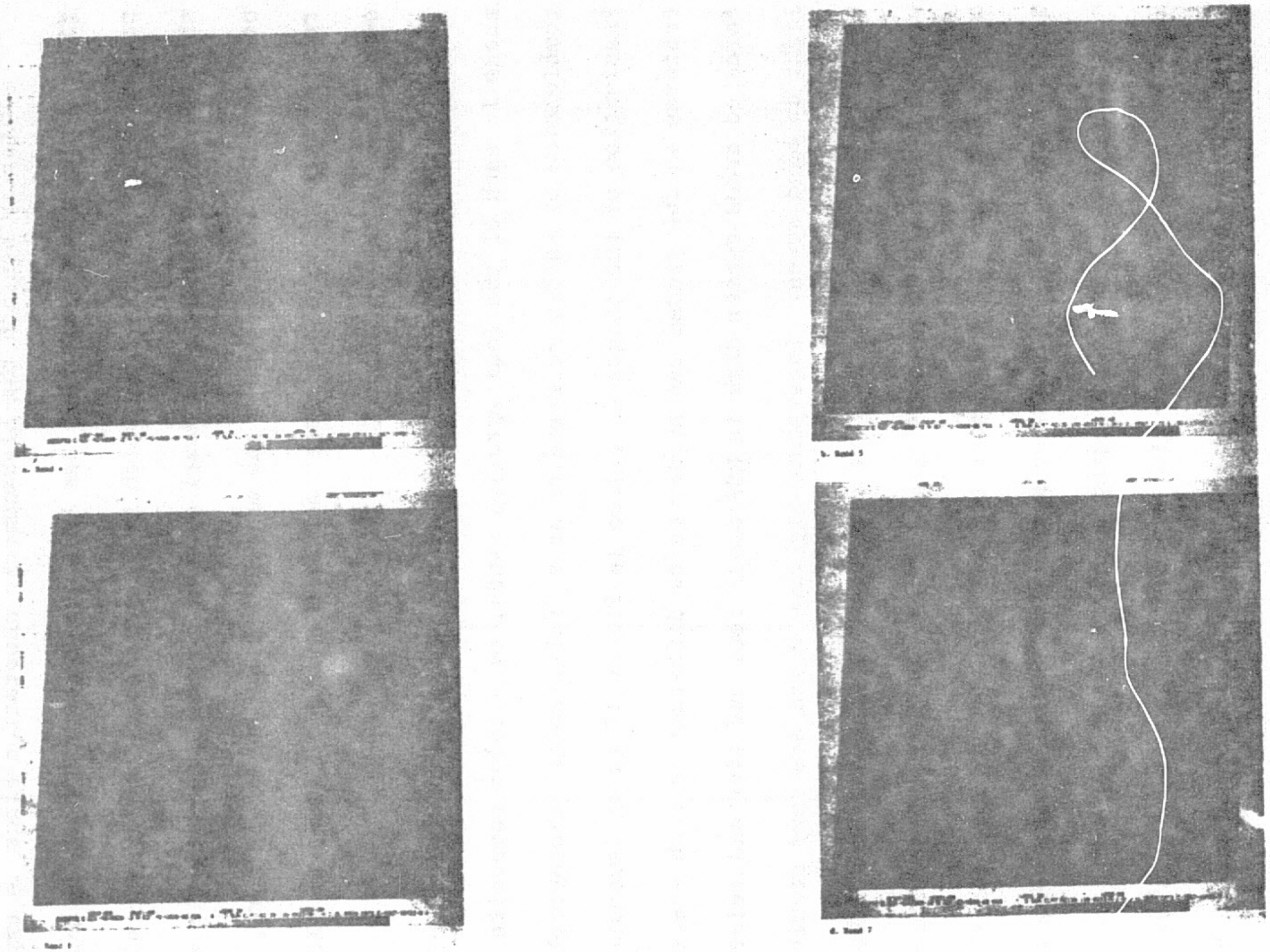

Figure 10 (a-d). An ERTS-I Scene of the Montgomery Area in MSS Bands Four, Five, and Seven.

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been obtained. The color composite images used were produced both photographically by the EROS data Center, Sioux Falls, South Dakota, and locally with the use of an I^2S Mini-Addcol color-additive viewer (Model 6000).

Color composite images are produced by projecting colored light through black-and-white transparencies and superimposing the resultant images. Two to four images may be used with varying hues and light intensities thereby highlighting or subduing certain physical or cultural features in the scene.

The scenes represented in Figure 10 a, b, and d (MSS bands four, five, and seven) were combined photographically to produce Figure 11. Three standard process colors were assigned to the bands in the order of the spectrum (band four, yellow; band five, magenta; band seven, cyan). The synthetic color representations of the real world colors result in the green portion of the spectrum (0.5 to 0.6 microns, band four) being imaged as yellow; the red portion of the spectrum (0.6 to 0.7 microns, band five) being imaged as magenta; and the infrared portion of the spectrum (0.8 to 1.1 microns, band seven) being imaged as blue.

The extensive red areas in Figure 11 result from the fact that growing vegetation occupying these areas radiates strongly in band seven and therefore is rendered as red because of the absence of cyan. Consequently, the intensity of red coloration is indicative of the degree of vigor of the green vegetation. Large urban areas assume a characteristic blue-green appearance due to the fact that these urban

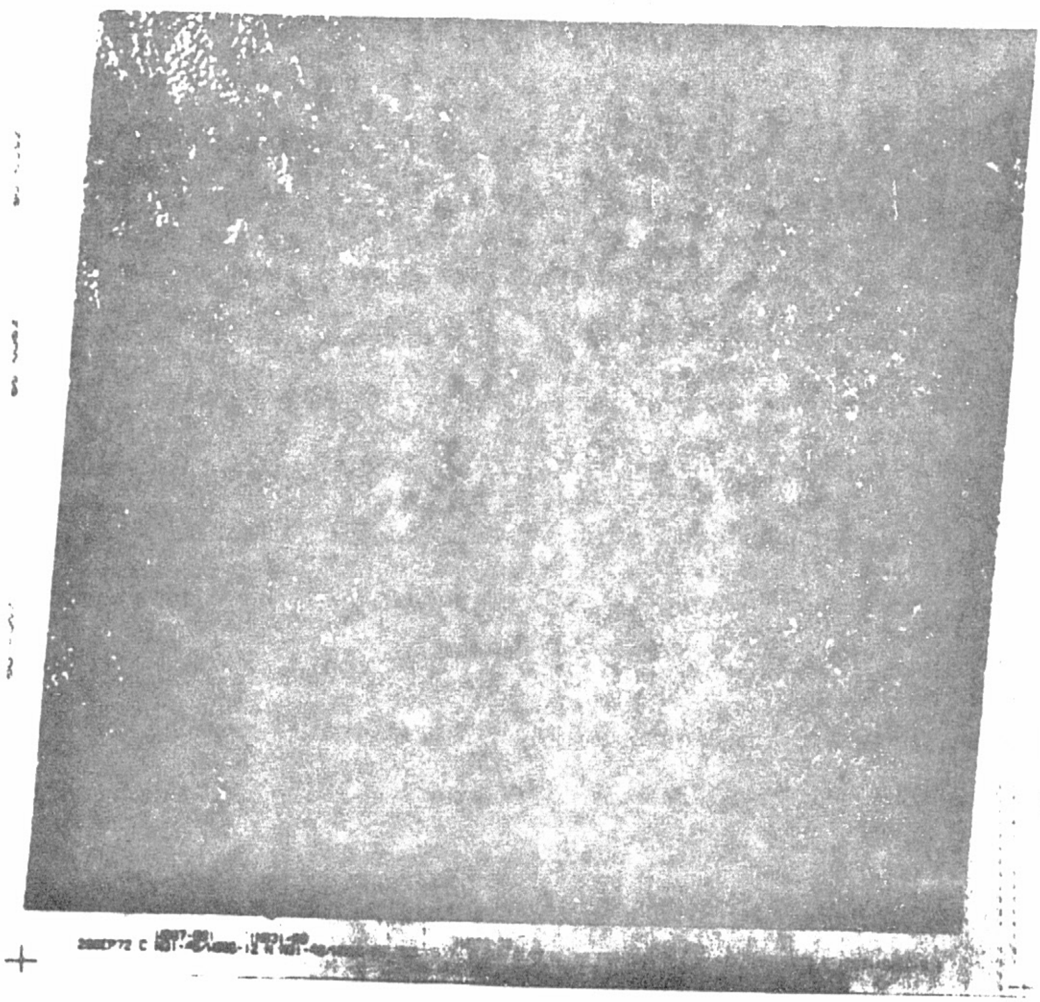

Figure 11. A False-Color Composite of the Montgomery Area Using MSS Bands Four, Five, and Seven.

areas have similar photographic density in bands four and five. Therefore, both yellow and magenta are attenuated and the urban complex appears in shades of blue.

PROJECT BACKGROUND

2.1 Alabama ERTS Project

The University of Alabama, in conjunction with the Geological Survey of Alabama and the George C. Marshall Space Flight Center, is conducting a vigorous program to determine the feasibility of using remotely sensed data from ERTS-I for (1) mapping land use and detecting land-use change, (2) the inventory and management of natural resources, and (3) the improvement of environmental quality in Alabama.[8] The realization of these goals requires the successful completion of the following:[9]

1) Identification and education of users regarding the potential benefits of space-acquired data.
2) Timely interpretation and dissemination of information to users in a form most amenable to their application.
3) Analysis of whether or not information gathered from ERTS-I imagery offers an improvement over more conventional sources of information relating to the user's decisions and actions in the management of natural resources and improvement of environmental quality.

Through a series of public and private meetings beginning in mid-1971 and continuing up to the present time, liaison was established with representatives of both private industries and public agencies

representing a wide spectrum of disciplines. These professionals (Table I) all expressed an interest in using remotely sensed data from ERTS-I. Public awareness is only the first step however, and must be followed by a conclusive demonstration that ERTS products are advantageous over alternative sources of information. This continuing process of demonstrating the usefulness of ERTS-I imagery, the prime consideration of the University of Alabama ERTS Project, is in itself the only criterion which will stimulate and sustain the demand for ERTS-I products.

To this end, the Alabama ERTS Project is subdivided into five distinct yet closely related research teams each led by an authority in his field and staffed by graduate and undergraduate research assistants. The individual research efforts are as follows:

1) Land use, mineral exploration, and geology: Professor Reynold Q. Shotts.
2) Environmental, hydrology, and water resources: Dr. George P. Whittle
3) Marine science: Dr. C. Everett Brett.
4) Date processing and data management: Dr. Edmond T. Miller.
5) Economics and user liaison: Dr. J. F. Vallery.

In addition, Mr. C. T. N. Paludan and Mr. Robert Cummings of the George C. Marshall Space Flight Center are working with ERTS in the areas of environmental considerations and data processing, respectively. From The Geological Survey of Alabama, Dr. James Drahovzal and colleagues are investigating the usefulness of ERTS-I imagery in the areas of geology, hydrology, water resources, geography, change detection, and energy

TABLE I

Professionals Expressing an Interest in Using ERTS-I Data

Urban Planners	Civil Engineers
Regional Planners	Chemical Engineers
Foresters	Agricultural Engineers
Geologists	Mining Engineers
Ecologists	Geographers
Hydrologists	Limnologists
Agronomists	Entomologists
Biologists	Architects
Physicists	Archaeologists
Astronomers	Demographers
Chemists	Lawyers
Agriculturists	University Faculty Members

resources. Close liaison has been established and maintained throughout this investigation between members of these three major research organizations. The results have been complementary.

2.2 Concurrent Investigations

2.2.1 Importance

Throughout the course of this investigation, especially since the launch of ERTS-I, information regarding the practical aspects of ERTS imagery was being received by the writer on almost a daily basis. In addition, he attended several symposia in order to become cognizant of what others were doing in applying ERTS-I data, and remotely-sensed data in general, to solving problems of the environment. Through correspondence, personal visits, formal meetings, and attendance at these symposia, he learned not only what others were doing, but also if what they were doing and how they were doing it could be utilized in this investigation. Many fruitful meetings were held with personnel of various planning and research agencies during the investigative period. Since the significant results of these meetings will be covered in the following section (2.3, Project Development), this section will primarily be a discussion of what other researchers were and are doing on investigations similar to ours.

2.2.2 Land-Use Studies

It was learned from presentations at the September 29, 1972, ERTS-I Symposium at the Goddard Space Flight Center, that MSS Bands four, five, and seven were the best suited for the production of a color

composite. Furthermore, through the interpretation of such a composite, many individual crop types and associated soil conditions could be identified.[10]

The study plan formulated for use in this investigation by which a full-frame analysis would be made prior to a detailed survey was reinforced by others at the symposium.[11, 12] Morely (1972) reported good results in identifying vegetation types in the McKenzie Delta using MSS bands five and six, an important criteria in mapping marketable forest reserves.[13] Simpson (1972) reported mapping land use in eight separate categories at the rate of thirty square miles per hour.[14] Even after enlarging the ERTS-I image four times, to a scale of 1:250,000, his claim of discriminating single-family from multi-family dwellings and commercial from industrial developments seemed somewhat extravagant. Nevertheless, some of his discoveries were encouraging at that stage in this investigation.

Many of the researchers stressed the importance of the I^2S Mini-Addcol color-additive viewer in their investigations; and demonstrations of its potentials were impressive. The lack of equipment funds prohibited its use in this effort however, although limited access to an I^2S Model 6000 Addcol viewer was obtained from the Marshall Space Flight Center, Huntsville, Alabama. Because of this lack of more sophisticated equipment, a literature survey was conducted to ascertain a suitable analytical procedure for use with ERTS-I imagery.

Simonett and Coiner (1971), using a grid overlay on simulated ERTS images, first attempted to record land use density by counting the number of gray levels within each cell. After determining this to be

unrealistic, land-use categories were defined and the number of land-use types per cell were recorded. They concluded from their study that ERTS would be most effective in areas where human impact is less and where large areas of homogeneous land use occur.[15] Aldrich, et.al (1970), used a dot grid to inventory forest cover using space-acquired data.[16] Similarly, Simpson, Yuill, and Lindgren (1972) described a procedure for coding land use off of RB-57 imagery using a grid overlay.[17] The procedure described therein was immediately recognized as being applicable to the analysis of ERTS-I imagery. Simpson (1970) offered many valuable techniques in the interpretation of high-altitude photographs for land-use mapping.[18] Many of his procedures especially those of orienting the grid, were significant in the development of the procedure used in this study for mapping both historic and ERTS-I land-use data.

Anderson (1973), using ERTS-I imagery to map wetlands in Georgia used photographic techniques to enlarge ERTS images up to a scale of 1:24,000 which he found suitable for thematic mapping.[19] Scale distortion and cost of photographic processing were judged to be too prohibitive for this investigation however.

F. C. Westin (1973) also used a mylar grid overlay to extract soils and land-use information from ERTS-I imagery.[20] He reported excellent correlation of soil associations mapped from ERTS and known ground truth.

Simpson (1973) reinforced the techniques used in this investigation.[21] Although he used ERTS-I imagery enlarged to a scale of

1:250,000, instead of the standard 1:1,000,000 image under magnification, his procedure of aligning the grid was very similar to that used here.

2.2.3 Change-Detection Studies

Most of the investigations cited in the previous section not only dealt with land use, but also with land-use change. The two are almost inseparable, especially when older maps or photographs are used for comparison. One of ERTS-I's attributes is its synoptic coverage which, when compared to previously taken scenes of the same area, may in itself demonstrate changing features and land-use patterns.

To date, most of the papers dealing with land-use change and change detection have been confined to urban change or change in a very small system.[22, 23] Few have ventured forth to measure land-use developments on a regional scale. Two who have, however, were Fitzpatrick and Lins (1972). They selected sites from ERTS-I imagery covering a 1600-square-mile area which they believed to be sites undergoing change.[24] In most cases, they were correct; yet, even this study was limited to detecting spectral anomalies within the image, and did not venture into trend prediction.

2.2.4 Optimum-Site-Location Studies

Very little has been done in using data acquired through remote sensing for optimum-site-location of a particular industry. The Federation of Rocky Mountain States, Incorporated, Denver, Colorado, has

developed a composite mapping program for optimum-site-location and has designed a software "preprocessor" to provide a "translator link" between interpreted remote sensor imagery and cellular maps.[25]

2.3 Project Development

Many of the objectives, procedures, and understandings of this investigation were developed through the daily operation of the research and close liaison with other investigators during the entire course of this study. To fully understand this developmental process and how it resulted in the objectives and procedures which will be described later, some history of this investigation's development will be given.

The first two weeks of January, 1972, were used to become familiarized with the project's purpose and scope and to decide on an approach to the initial task of preparing a land-use map of Alabama to be used as a base map on which to superimpose ERTS-I data. It was discovered at this point that no land-use maps were available for the entire State of Alabama. Those maps that did exist were of many different scales and land-use classifications and were, for the most part, outdated. Hence, it was decided to use part of an eight-month grant awarded in January, 1972, by the NASA/Marshall Space Flight Center in the preparation of a consistent, detailed, and accurate land-use inventory for all 67 counties in Alabama.

On January 11, 1972, a meeting was held with officials of the Soil Conservation Service (S.C.S.) at Auburn, Alabama, for the dual purpose of investigating the mechanics by which the S.C.S. was preparing its land-use maps and to establish close liaison with that

agency. Their rectangular cell shape and size later proved inconvenient and their computer mapping program (MIADS) was too restricted for our purposes. The S.C.S. procedure of plotting land-use data from air photo mosaics onto transparent grid overlays did prove feasible however, and was employed in preparing the base map.

On February 3, a meeting was held with officials of NASA's Marshall Space Flight Center to investigate their procedure of land-use mapping and computer applications. It was learned there that NASA employed the Universal Transverse Mercator (UTM) coordinate system and that ERTS data would be referenced to UTM coordinates. Therefore, it was decided to utilize the UTM system in our state-wide land-use survey. It was also resolved to code land use using categories which were compatible with expected ERTS resolution capabilities. The five primary land-use categories tentatively agreed upon at the meeting included: (1) urban and built up, (2) agricultural, (3) forestland, (4) water, and (5) barren land.

The next two weeks were devoted to developing the grid and cell size to overlay the air photo mosaics. A square cell representing one square kilometer was agreed upon. In addition, a procedure for accurately orienting the grid on the air photo mosaics was developed. The procedure, to be detailed later, involved overlaying the grid on a county highway map to derive the UTM coordinates and reference points, and then positioning the grid over the mosaic of the same county such that the reference points plotted on the grid corresponded to those features on the air photo mosaic.

To facilitate this procedure, the UTM parallels and meridians were plotted on all 67 county highway maps. This process was completed on April 3, 1972. Coding of land use from U. S. Department of Agriculture air photo mosaics began on April 4, 1972, and was completed on October 6, 1972.

On November 9, the writer formulated and submitted three tentative thesis objectives. These were based in large measure on the preparatory work completed on the ERTS Project as of that date and before ERTS-I imagery had been received and analyzed.

Shortly thereafter, the first images from ERTS-I were received. These scenes were of the "L" orbit and were acquried by the satellite on September 11, 1972. The quality of this first set of data was disappointing and ultimately led to a meeting on November 15, 1972, with personnel of the Marshall Space Flight Center. It was determined that stricter and more consistent control of image duplication was required to resolve the data quality problem. Image quality thereafter was somewhat improved.

An initial analysis of the ERTS imagery was conducted; and, even though poor in quality, the images yielded more information than originally thought possible. There were even instances of surprising detail, allowing definition of a number of interesting and even significant features.

The analysis of ERTS-I imagery began on a systematic basis in late January, 1973. Scene analyses were first undertaken in order to provide an overview of the entire scene and to indicate potentially troublesome areas before the cell-by-cell coding of land use was initiated.

A symposium dealing with practical applications of ERTS-I imagery was held March 5-9, 1973, at New Carrolton, Maryland. Many of the papers presented were of great interest and reinforced the methodology of this investigation. From this symposium and from the results of this investigation, it was clearly evident that mapping land use from ERTS-I imagery was indeed feasible.

To demonstrate both the feasibility of extracting land-use information from ERTS-I data and also its practicality, it was decided in late March, 1973, to formulate a composite mapping program using timely land-use data from ERTS-I in locating optimum sites for industries and/or services. A meeting was held on May 30, 1973, with personnel of the offices of State Planning and Industrial Development of the Alabama Development Office in Montgomery, Alabama. Although they had not progressed in the direction of a composite mapping program for optimum-site location, they expressed a keen interest in its development. They were of some help in determining which industries were best suited for the target study area, tentatively envisioned at that time as containing approximately ten to twelve counties in southeastern Alabama. They were, however, unable to suggest which criteria most affected the location of industrial sites.

In a meeting on May 31 with Dr. J. F. Vallery and Dr. Larry Davis of Economics and Finance, College of Commerce and Business Administration, The University of Alabama, it was suggested and thereupon agreed that the basic criteria in optimum site location by the computer composite mapping program should be restricted to those physical parameters detectable by ERTS-I (proximity to urban centers, access routes, ground

cover, water availability, etc.) and to relegate socio-economic factors to supplemental secondary information. It was felt that the value and practicality of ERTS-I imagery would be maximized by applying it to the location of the most suitable sites for industrial, municipal, and recreational developments.

2.4 Project Objectives

The objectives of this investigation were designed specifically to be in conjunction with the over-all goals of The University of Alabama ERTS Project discussed in Section 2.1. Objectives were chosen which would not only demonstrate the feasibility of gathering land-use information from ERTS-I data, but which would also demonstrate its practicality and even preferability over other forms and sources of data. The reader should realize that these objectives were not spontaneously written, but were composed, edited, written, and rewritten many times over a period of almost seven months. From their conception in late 1972, the objectives were developed, defined, and redefined as the project gained momentum. Only after detailed analysis of the first ERTS-I images had been completed were the objectives of this effort clearly envisioned.

The first of this project's objectives was to produce an accurate and timely land-use inventory of a predetermined target study area using photographic interpretation techniques in assessing multispectral scanner data from ERTS-I. This objective was intended to test the feasibility of gathering accurate, timely land-use data from ERTS-I imagery for comparison with and update of the historic data gathered in the pre-launch phase of the project.

Since change in any area could have far-reaching effects, it is imperative that we be able to understand, monitor, and thus predict patterns of change. Realizing that general land use is an excellent indicator of the nature and degree of regional change,[26] the second objective of this investigation was to produce maps of change for any land-use category or combination of categories by comparing historical land use data with that obtained from ERTS-I. Achievement of this objective would hopefully reveal specific patterns of development, on the basis of which, certain trends and recommended courses of action could be determined.

The third objective, that of obtaining spectral signatures of both physical and cultural features through the correlation of ERTS-I data with existing ground-truth information, is actually a by-product of and part of the basic structure of the entire study. At the heart of any analysis of remotely sensed data is a clear understanding of the sensor's resolution capability, the general types of ground cover imaged, and the ultimate purpose of the analysis. Determining spectral signatures of objects on the ground is not merely the process of assigning a certain level of gray to a feature forever more to be associated with that feature. Topography, climatic conditions, sun angle, and image processing all play a significant role in determining what a feature's spectral response will be; hence, the same features even just a few kilometers apart may possess very different spectral signatures. It is, rather, the response of features relative to that of the surrounding ground cover which is so important.

The fourth and final objective of this investigation depends upon the successful completion of the first three objectives and yet, is considered the most important of the four. The objective is to demonstrate the usefulness of the Earth Resources Technology Satellite as a tool in land-use inventory, management, and planning. Successful completion of this objective via the afore-mentioned composite mapping program for optimum-site location would not only demonstrate the practicality of the ERTS-I program, but would also be of significant benefit to public planning agencies, private industries, and policy makers in their planning and regulatory functions.

2.5 Target Study Area

2.5.1 Geographical Description

The target study area for this investigation consists of nineteen counties in the southeastern corner of Alabama (See Figure 12). These are: Autauga, Elmore, Macon, Lee, Lowndes, Montgomery, Bullock, Russell, Butler, Crenshaw, Pike, Barbour, Conecuh, Covington, Coffee, Dale, Geneva, Henry, and Houston counties. The total area of all nineteen counties comprises over 25 percent of Alabama's entire land area of 135,289 square kilometers as given in Table II.

Four State Planning and Development Districts (5, 7, 9, and 10) of the Alabama Development Office (ADO) are represented in whole as well as one county from District 6, Conecuh County, Figure 13 illustrates the configuration of the four districts within the target study area. Conecuh County was included so that the target study area would encompass

Figure 12. Nineteen County Target Study Area.

TABLE II

Areal Data on Nineteen-County Target Study Area

County	Area (km^2)	Percent of Target Area	Percent of State Area
Autauga	1583	4.67	1.17
Barbour	2361	6.96	1.74
Bullock	1634	4.82	1.20
Bulter	2015	5.94	1.49
Coffee	1743	5.14	1.29
Conecuh	2124	6.26	1.57
Covington	2734	8.06	2.02
Crenshaw	1590	4.69	1.18
Dale	1393	4.11	1.03
Elmore	1672	4.93	1.24
Geneva	1441	4.25	1.06
Henry	1527	4.50	1.13
Houston	1542	4.55	1.14
Lee	1604	4.73	1.18
Lowndes	1872	5.52	1.38
Macon	1617	4.77	1.20
Montgomery	2055	6.06	1.52
Pike	1710	5.04	1.26
Russell	1694	5.00	1.25

5. South Central Alabama Development Commission
6. Alabama and Tombigbee Rivers Regional Planning and Development Commission.
7. Southeast Alabama Regional Planning and Development Commission
9. Central Alabama Regional Planning and Development Commission
10. Lee County Council of Local Governments

Figure 13. Alabama Development Office State Planning Districts Corresponding to the Target Study Area.

all of the Alabama State Planning and Industrial Development Board Area Number 2 as given in Figure 14. An obvious effort was made to include as many state planning districts as possible in the target study area for the purpose of establishing a working relationship with those districts and to demonstrate to them the applicability of ERTS-I data in their own areas. In addition, three U.S.D.A. Soil Conservation Service Areas are represented. All counties of Area 5 are included as are seven counties of Area 4, and one county of Area 6 (See Figure 15).

Most of the nineteen-county area is covered by ERTS-I scene K-3 (See Figure 16). Three additional scenes were required for complete coverage, however: K-2, L-3, and J-3. These four scenes are represented in mosaic form in Figure 17.

2.4.2 Regional Description

The area under investigation lies almost entirely within the coastal plain of Alabama, characterized primarily by a moderate topography (10 to 25 percent slope) (See Figure 18). Subsurface geology includes Mesozoic shales, clays, and sandstones in the northern portion and Cenozoic limestones, sandstones, and loose agglomerates in the southern portion. Paleozoic metamorphic and igneous rocks are confined to the northern halves of Elmore and Lee counties.

In areas underlain by relatively easily-eroded shales, clays, and chalks, cleared agricultural land prevails with forests lining the rivers and streams. Conversely, in areas overlying the more resistant sandstones, uninterrupted forest crown cover occupying the ridges stands out vividly in contrast to the cleared agricultural land occupying the surrounding valleys.

Figure 14. State Planning and Industrial Development Board Area No. 2. (Fantus, 1966)

Figure 15. USDA Soil Conservation Service Areas Corresponding to the Target Study Area.

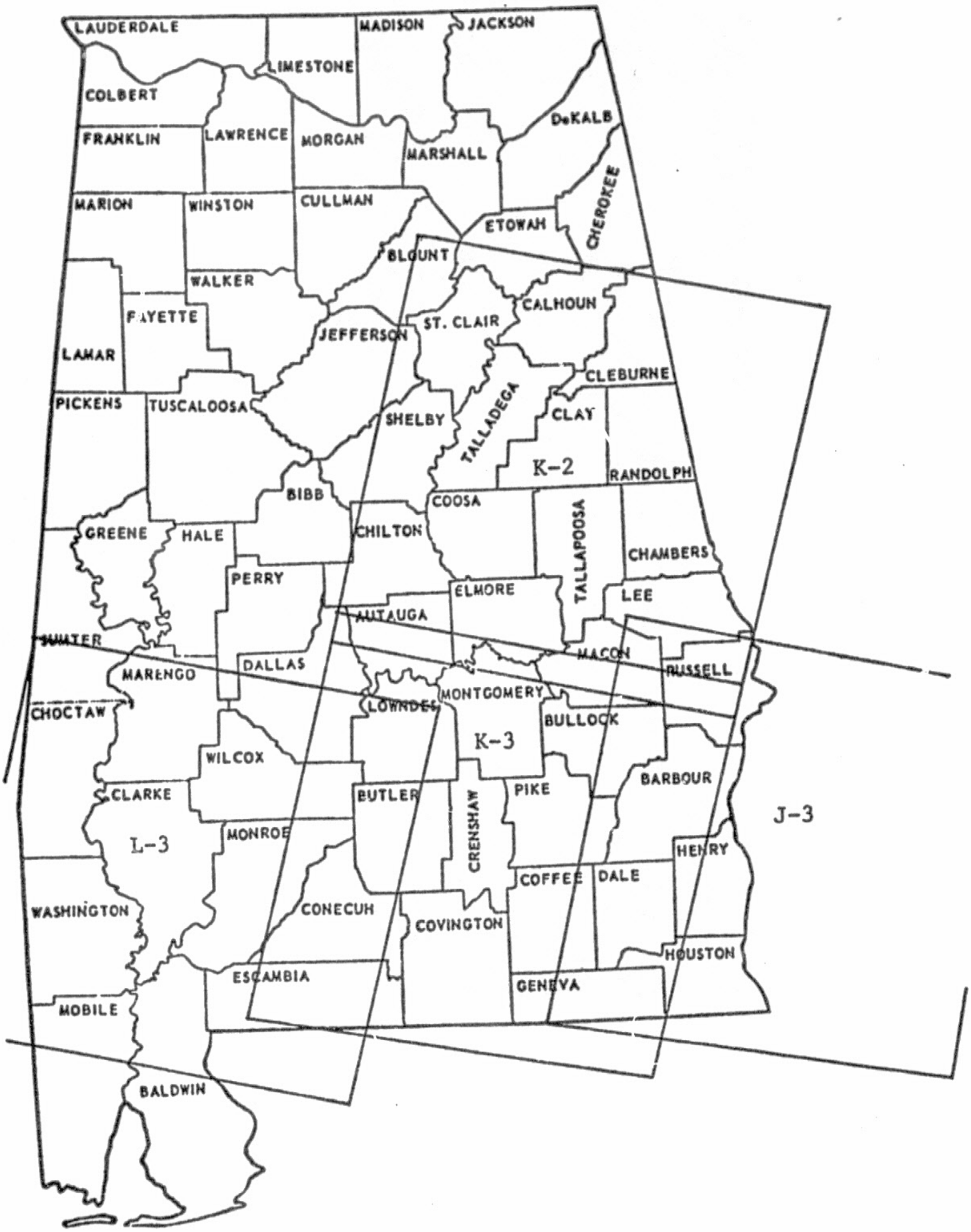

Figure 16. ERTS-I Scenes Covering
Target Study Area.

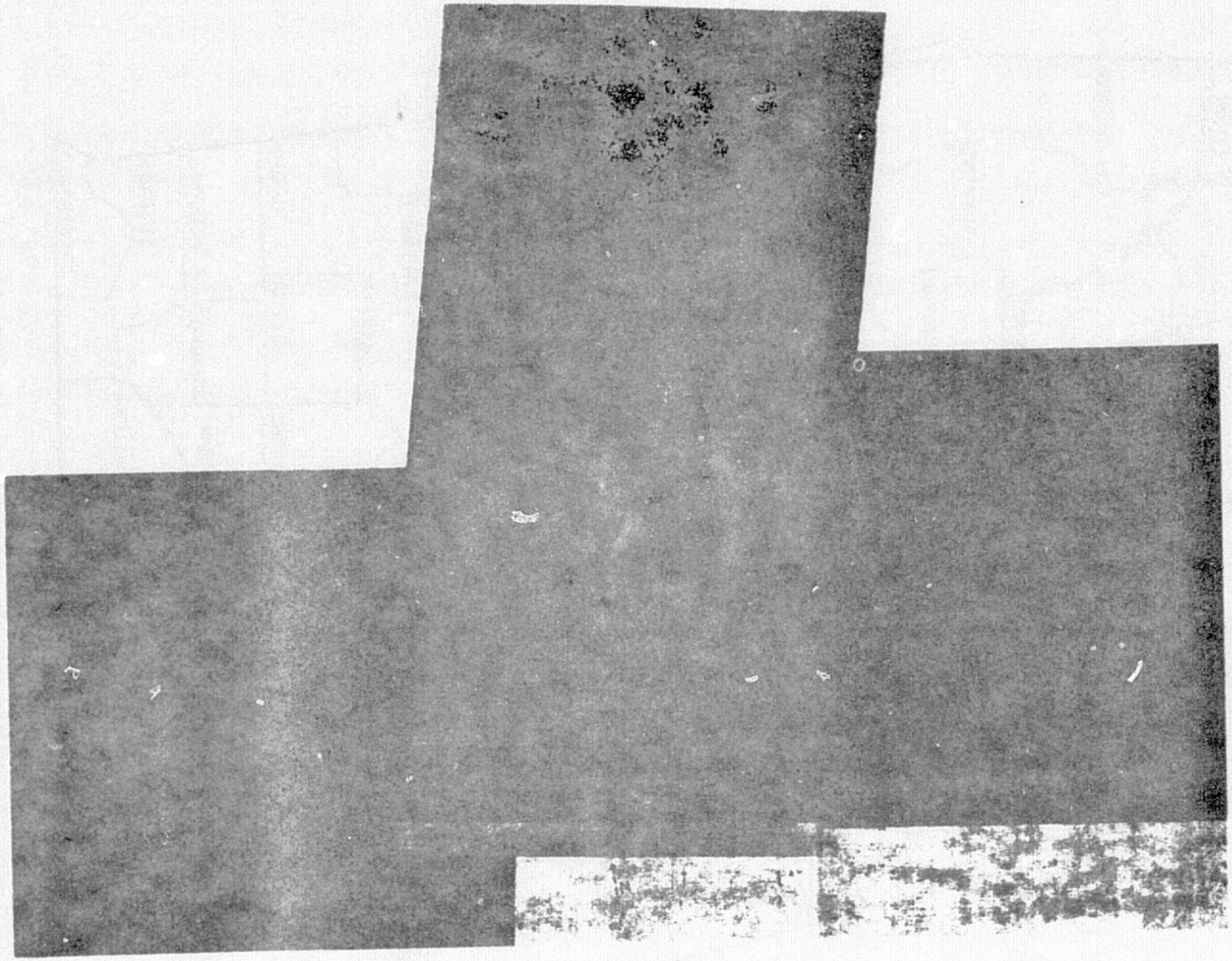

Figure 17. Mosaic of ERTS Images Covering Target Study Area.

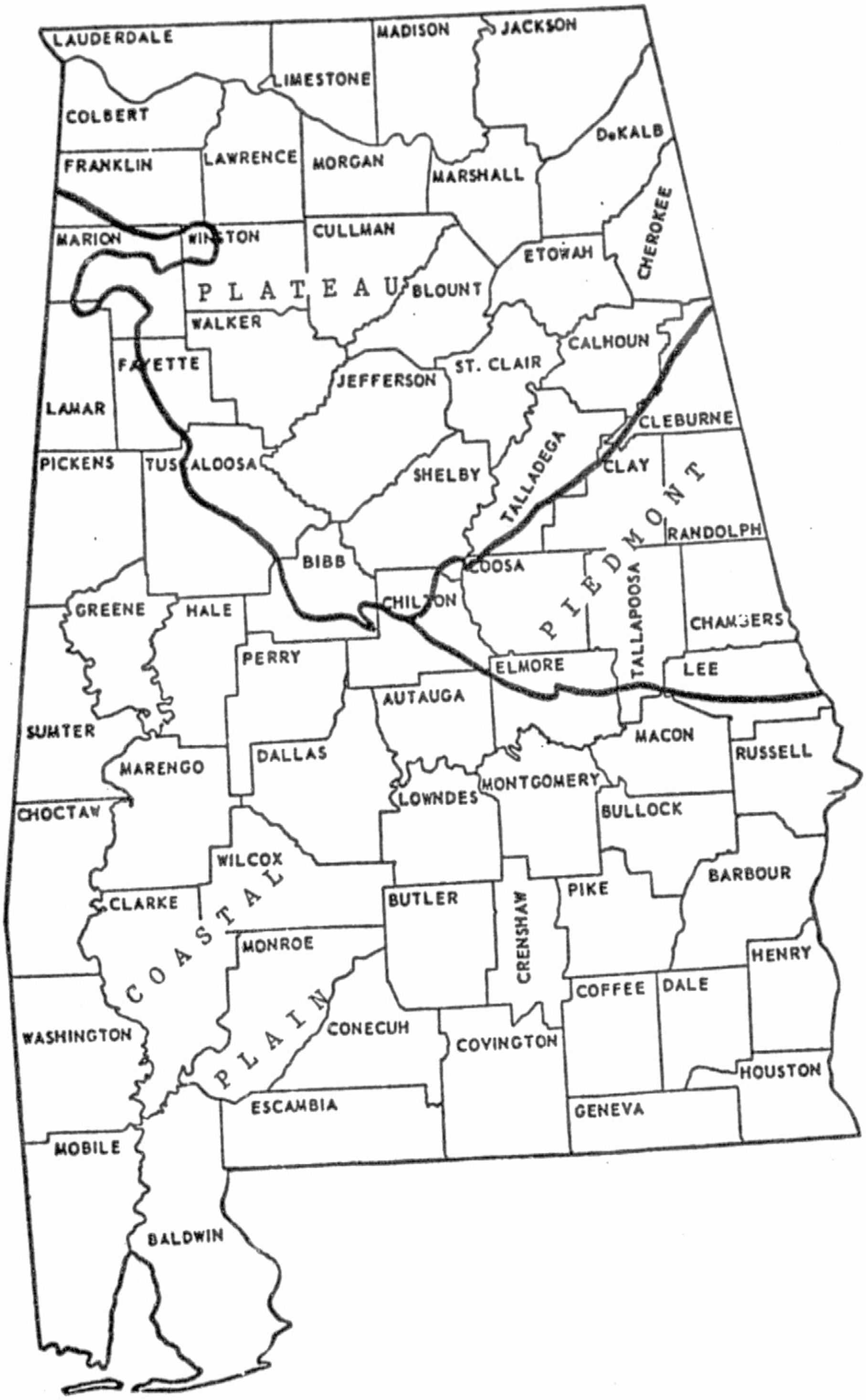

Figure 18. Geomorphic Regions of Alabama.

The Alabama, Conecuh, Tallapoosa, Choctawhatchee, Coosa, and Chatahoochee rivers dominate the area's drainage system and were clearly visible on the ERTS-I images in Figure 17. In addition, many smaller rivers were inferred from dendritic drainage patterns. Many multi-purpose lakes have been formed along these rivers including Lake Mitchell on the Coosa River in Autauga County; Lake Martin on the Tallapoosa River in Elmore County; Lake Harding and W. F. George Reservoir on the Chatahoochee River in Lee and Henry Counties respectively; and smaller lakes such as Point "A" Lake and Gantt Reservoir on the Conecuh River in Covington County and Lake Tholocco on a tributary of the Choctawhatchee River in Dale County.

A preliminary evaluation of the ERTS-I scenes covering most of the target study area[27, 28] revealed the major urban areas of Montgomery, Dothan, Auburn-Opelika, as well as the smaller towns of Andalusia, and Tuskegee. Connecting routes between many of these cities evident on ERTS imagery included I-65, I-85, US-231, US-80, and US-29. Other cities outside these scenes which were easily detected were Phoenix City and Eufaula on the Chatahoochee River.

The great diversity of land-use types was a prime consideration in the selection of southeastern Alabama as the target study area. All land uses detectable by ERTS-I are represented. In addition, industrial growth in the area over the past ten years, a critical factor in urban growth, was very substantial.[29] This was also significant in the choice of target study areas, in that rapid urban growth as well as the increasing cultivation of previously forested areas facilitate change detection on a regional scale. Another important factor in its selection was previous personal experience in the area.[8]

LAND-USE COMPILATION

3.1 Purpose of Land-Use Compilation

To make competent decisions, Alabama state planners and policy-makers must have accurate, timely information on the many interrelated aspects of their activities. Land use is just one of these aspects, but one which in recent years has become progressively more important in solving the problems of urban sprawl, forest depletion, strip-mining, and other problems of the total environment. Land use reflects man's impact on the environment in a readily discernable and vivid way.

Land development and use in the United States has historically been haphazard at best with no apparent planning or forethought. The land-use plans that were formulated and even adopted by various levels of government often were not implemented or otherwise failed.[30] To initiate wise land-use planning practices and thus improve the economy and environmental quality of the area, it is imperative that planners and policy-makers understand land-use trends and be able to monitor and predict patterns of land-use change.

Extraction of land use data from two different time frames with subsequent comparison of the data sets facilitates the detection of land-use change, especially on a regional basis. The purpose of compiling a historic inventory of land-use information for the entire State of

Alabama for the time period 1961 to 1971 was actually twofold: (1) it provided the state with its first state-wide accurate, consistent, and timely land-use maps, and (2) it provided the heretofore almost non-existent "historic" land use data base for subsequent comparison with land-use data later extracted from ERTS-I imagery.

The extraction of land-use data from ERTS-I imagery served a plural function. It provided a means of determining the feasibility of performing such an extraction accurately and efficiently, while at the same time rendering timely information concerning the utilization of our greatest natural resource, the land. The inventory of land use from ERTS-I scenes also provided a means of assessing land-use change when compared with historic data and will in itself serve as a data base with which to compare subsequent data from ERTS-I and its descendents.

3.2 Land-Use Classification Scheme

No ideal classification of land use has yet been developed or probably ever will be. Each land-use classification in existence today was designed with a specific purpose, a certain need, in mind. A classification system so designed must meet most of the needs of the users or face rejection.

In developing their land-use classification scheme for use with remotely sensed data, Anderson, et.al (1972), made the distinction between "land use" and "land cover."[31] Land use refers to man's activities on land directly relating to the land while land cover denotes the the natural vegetation and cultural construction on the surface.

Obviously, some of man's activities directly influence the type of land cover, e.g., agriculture, urban growth, strip-mining, and water management. Other activities, however, such as hunting and fishing cannot be determined by remote sensing; and an area utilized by hunters and fishermen would better be classified as forests and lakes. Land cover therefore is the basic criterion in the first and second levels of the land-use classification described by Anderson and used in this investigation.

All primary levels in Anderson's classification would seem to be distinct and separate entities in themselves, but even such a supposedly obvious feature as a water-land interface can become impossible to map in areas of periodic flooding or in marshes. Equally difficult to delineate is the urban-rural interface in winter when the barren agricultural fields give much the same spectral response as paved parking lots and streets. Problems of this type are inherent in any classification scheme and must be considered in the final analysis.

Anderson's land-use classification system was adopted for use in this study because (1) it provided continuity with the majority of other researchers in the United States, (2) the classification was considered compatible with the resolution capabilities of the sensors aboard ERTS-I, and (3) the scheme simplified identification, reduced interpretation errors, and provided a format which could easily be modified in order to make it compatible with other land-use classification systems. The land-use classification produced by Anderson, et.al, for the Inter-Agency Steering Committee on Land Use Information and Classification is represented in Figure 19.

First Level	Second Level
Urban and Built-up	Residential Commercial and Services Industrial Extractive Major Transport Routes and Areas Institutional Strip and Clustered Settlement Mixed Open and Other
Agricultural	Cropland and Pasture Orchards, Groves, Bush Fruits, Vineyards and Horticulutral Areas Feeding Operations Other
Rangeland	Grass Savannas (Palmetto Prairies) Chaparral Desert Shrub
Forestland	Deciduous Evergreen (Coniferous and Other) Mixed
Water	Streams and Waterways Lakes Reservoirs Bays and Estuaries Other
Nonforested Wetland	Vegetated Bare
Barren Land	Salt Flats Sand (other than beaches) Bare Exposed Rock Beaches Other
Tundra	Tundra
Permanent Show and Ice Fields	Permanent Snow and Ice Fields

Figure 19. Anderson's (1972) Land-Use Classification Scheme.

All land use in Alabama, both past and present, was classified according to six of the first level categories in Figure 19, namely: urban, agricultural, forest, water, barren land, and nonforested wetland. Restricting the classification to these six categories facilitate accuracy, consistency, and speed.

The aforementioned six Level I land-use categories are further defined below in order to provide the reader with a better understanding of what was considered as being in each of these six land-use categories. As previously mentioned, the same six categories representing a somewhat generalized level of classification and interpretation were utilized in coding land-use information from both air photo mosaics at a scale of 1:63,360 and ERTS-I imagery at a scale of 1:1,000,000. For the former, the classification undoubtedly could have been much more refined, including sub-categories in Level II and even Level III; and for the latter, great effort was often involved in discriminating between even the Level I land-use categories.

Each of the following definitions necessarily was conceived early in the land-use coding phase of the project. The process did not stop there however; the land-use categories were scrutinized and redefined on a daily basis as problem areas were encountered. Likewise, the initial analysis of ERTS-I imagery imposed new stresses on the classifications of land cover and in some cases reduced the number of Level I categories detectable to four while at the same time rendering information about second and even third level land use. The number of land-use categories used or imposed was due to the geographic area under study, the atmospheric conditions at time of acquisition by the

satellite, the level of land-use complexity per cell, the amount of distortion and "noise" due to data transmission and photographic aberations, and the purpose for which the analysis was being made.

The Urban and Built-Up land-use category includes all areas of intense structural development such as cities, towns, villages, ribbon developments along roads and waterways, power plants, and small clustered developments around major highway interchanges. Areas lying within an urban area, which otherwise would have been classified according to another of the Level I categories, i.e., forest land, were coded as urban and considered to be parks or low density residential areas. Highways were not included in any of the land-use categories and were not coded. The patterns of other land uses, however, which were to some extent dependent on highway development, did indicate the highway's presence.

Agricultural land was a category given to almost all nonforested land not occupied by cities, water, or extractive industries. In some instances, a distinction could be made between croplands and other nonforested land on the basis of their geometric shapes.

Forest lands were perhaps the least difficult of all the land uses, with the exception of water, to recognize; although delineation of the forest-nonforest interface was often very difficult. Also included in this category were areas devoid of trees but located in the midst of expansive forests. This is particularly true in Alabama where large blocks of forest land are cut and replanted every twenty to thirty years. No distinction was made as to whether the trees were deciduous or evergreens, although this distinction was sometimes feasible.

All areas coded as Water include areas that are persistently inundated. Streams not actually visible but only inferred were not coded as such but were included within the land use in which they were found. No distinction was made between fresh and saline water or between natural lakes and man-made reservoirs, nor was the intended use of the water body or stream indicated.

Nonforested wetland referred to those areas where little or no forest crown was visible and where standing water was evident or strongly inferred. This category was usually deleted in the actual coding process since it was contained in only a few of the southern-most counties.

The Barren Land category was restricted to beaches and sand bars, bare rock exposures, strip-mined areas, borrow pits, and rock quarries. Land that was barren due to agricultural tillage and urban expansion was not included in this category.

Many Level II and even Level III categories were detectable on ERTS-I images at a scale of 1:1,000,000, but were classified according to their respective Level I categories to facilitate land-use mapping and change detection on a regional scale. While the classification used was very broad and helpful, it did not take into consideration some of the characteristics peculiar to ERTS-I imagery. Therefore, the classification scheme contained in Figure 20 was developed for use with ERTS imagery at least on local levels.

This classification was formulated directly out of this investigation of ERTS-I imagery and considers only those land-use features which are readily recognizable. It also provides a means of

I. URBAN

   A. Urban Core

   B. Noncore (residential)

II. RESOURCE PRODUCTION

   A. Agricultral

   B. Forest

      1. Continuous

      2. Discontinuous

   C. Extraction

III. TRANSPORTATION

   A. Motoring

      1. Primary

      2. Secondary

   B. Railroads (?)

   C. Airports

IV. WATER RESOURCES

   A. Rivers and Lakes

      1. Fresh

      2. Saline

      3. Turbid

      4. Transitional

   B. Marshland

Figure 20. A Feasibile Land-Use Classification Scheme for Use with ERTS Imagery.

discriminating between turbid water (either fresh or saline) and non-turbid water, a condition which is very apparent on MSS 4 (spectral green) and MSS 5 (spectral red) as the ERTS-I scene of Mobile Bay depicted in Figure 21 clearly indicates.

Classifying airports as a third level land-use category, was considered misleading considering their size and importance, and hence, they were classified under the general heading of transportation in Figure 20. A question mark was placed after railroads under "transportation," because to date, no railroad lines have definately been identified. They are included here, however, in the event that they are detected later using more sophisticated equipment.

3.3 Grid System and Cell Size

One of the primary accomplishments of the entire Alabama ERTS Project has been to summarize quantitatively the land-use information from the air photo mosaics and ERTS-I images in as clear and useful a form as possible. It was obvious at the start that the first step had to be the definition of an area or a series of areas (cells) and to describe them in terms of land-use information. Various grids were available for use: arbitrary grids based on a certain number of acres, square miles, or a portion of a topographic map, the Alabama state plane coordinate system, or the Universal Transverse Mercator grid.

For the purposes of this investigation, the selection of the Universal Transverse Mercator (UTM) grid system was a fairly easy one. The Alabama state plane coordinate system was considered unduly awkward for two reasons: (1) the state was divided into two separate zones, and

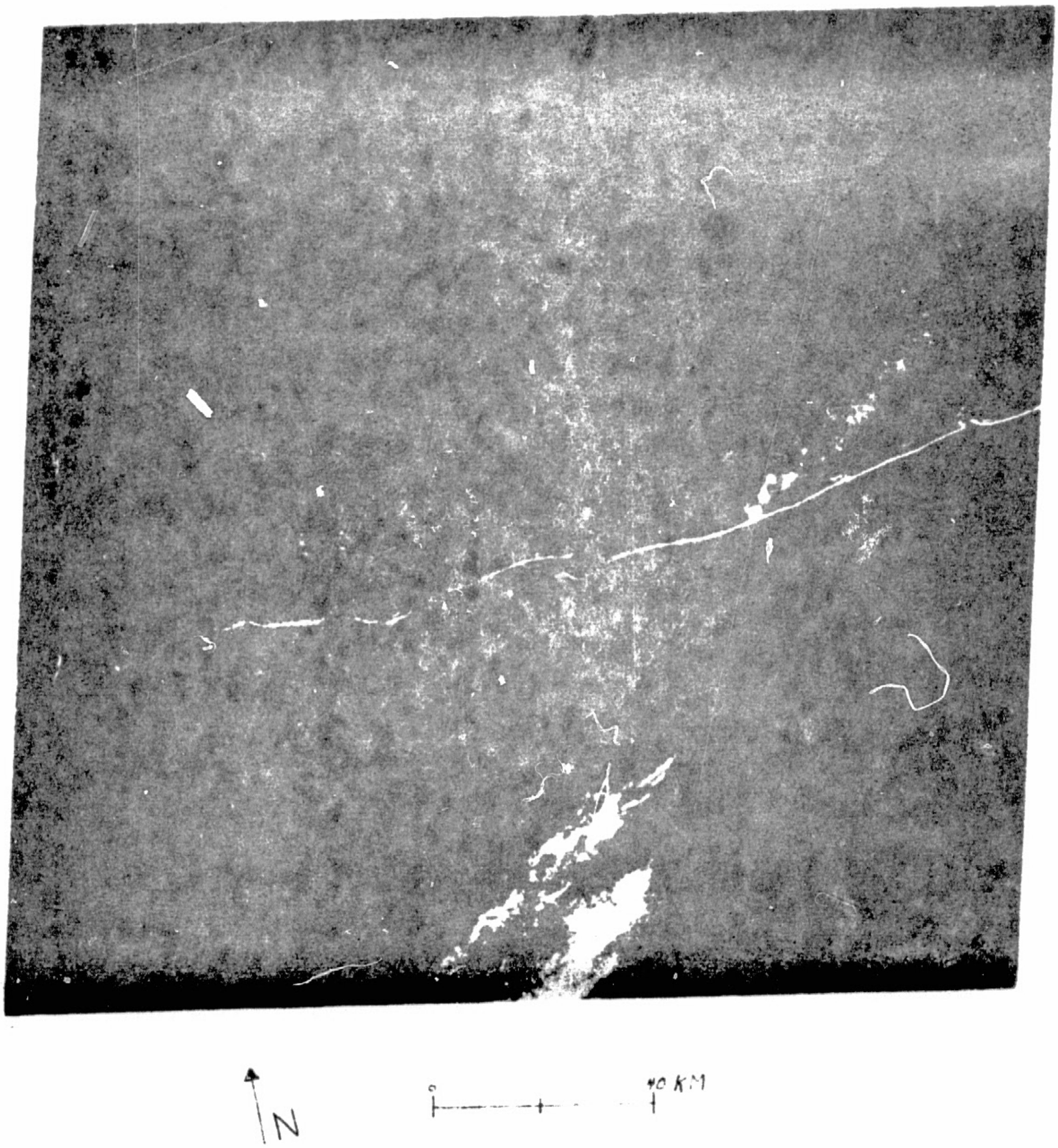

Figure 21. Monitoring of Turbidity in Mobile Bay by ERTS-I.

(2) the grid was measured in feet. In contrast, the UTM grid fits Alabama entirely into one zone (Zone 16, see Figure 22). The UTM grid within each zone is referenced to a central meridian which, for Zone 16, is 87 degrees west longitude designated as the 500,000 meter meridian. Values of meridians west of this line within Zone 16 decrease, while values of those east of the 500,000 meter base line increase. The values of the UTM parallels increase from zero at the equator northward. Figure 23 illustrates the UTM, Zone 16 grid system superimposed on a map of Alabama. Within this system, almost any size of grid cell can be selected.[32] Another attraction of the UTM system is its world-wide application, an important feature should the metric system be adopted in this country. Furthermore, each UTM grid unit is square and of constant size which facilitates computer analysis and display. The fact that remotely sensed data from ERTS-I was to be referenced according to the UTM system was also a prime consideration in its selection.

After selecting the grid system to be used, the exact cell size was determined. The prime considerations in determining optimum cell size were the amount of information required, minimum resolution of ERTS-I imagery, and the amount of time required. For the purpose of coding land-use information from air photo mosaics at a scale of 1:63,360, a one square kilometer cell size was selected (15.8 millimeters square at that scale). This size of cell allowed technicians to pencil in twelve digits comfortably while at the same time not compromising the amount of information coded by enlarging the cell size. The one square kilometer cell size was again employed in gathering land-use data from ERTS-I imagery. The scale of the imagery and its minimum

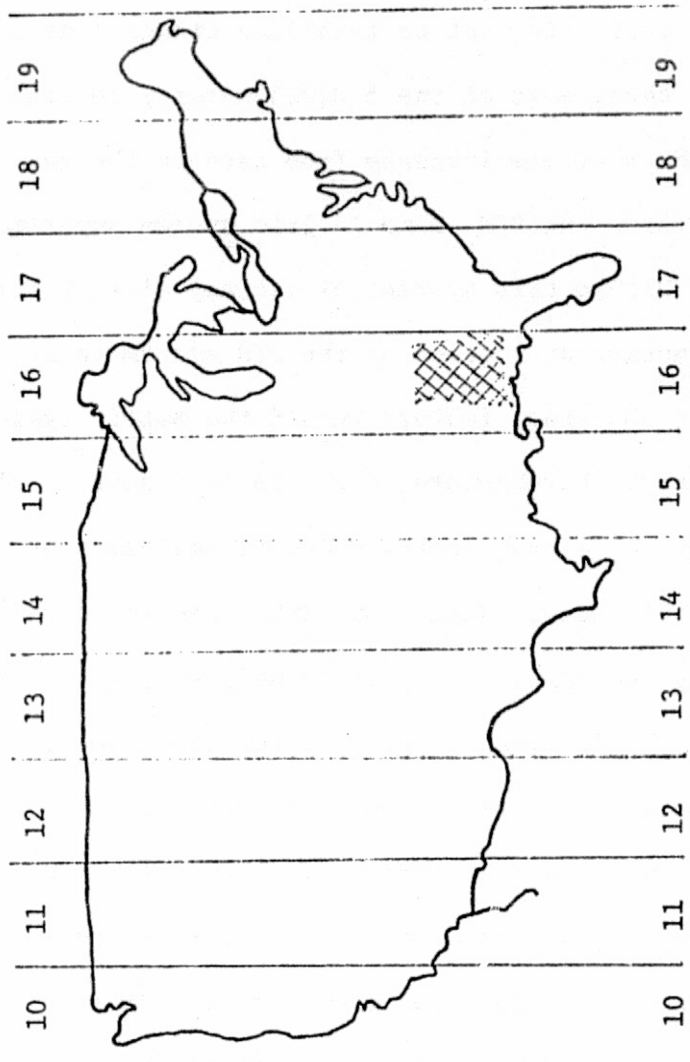

Figure 22. UTM Zones of the United States.

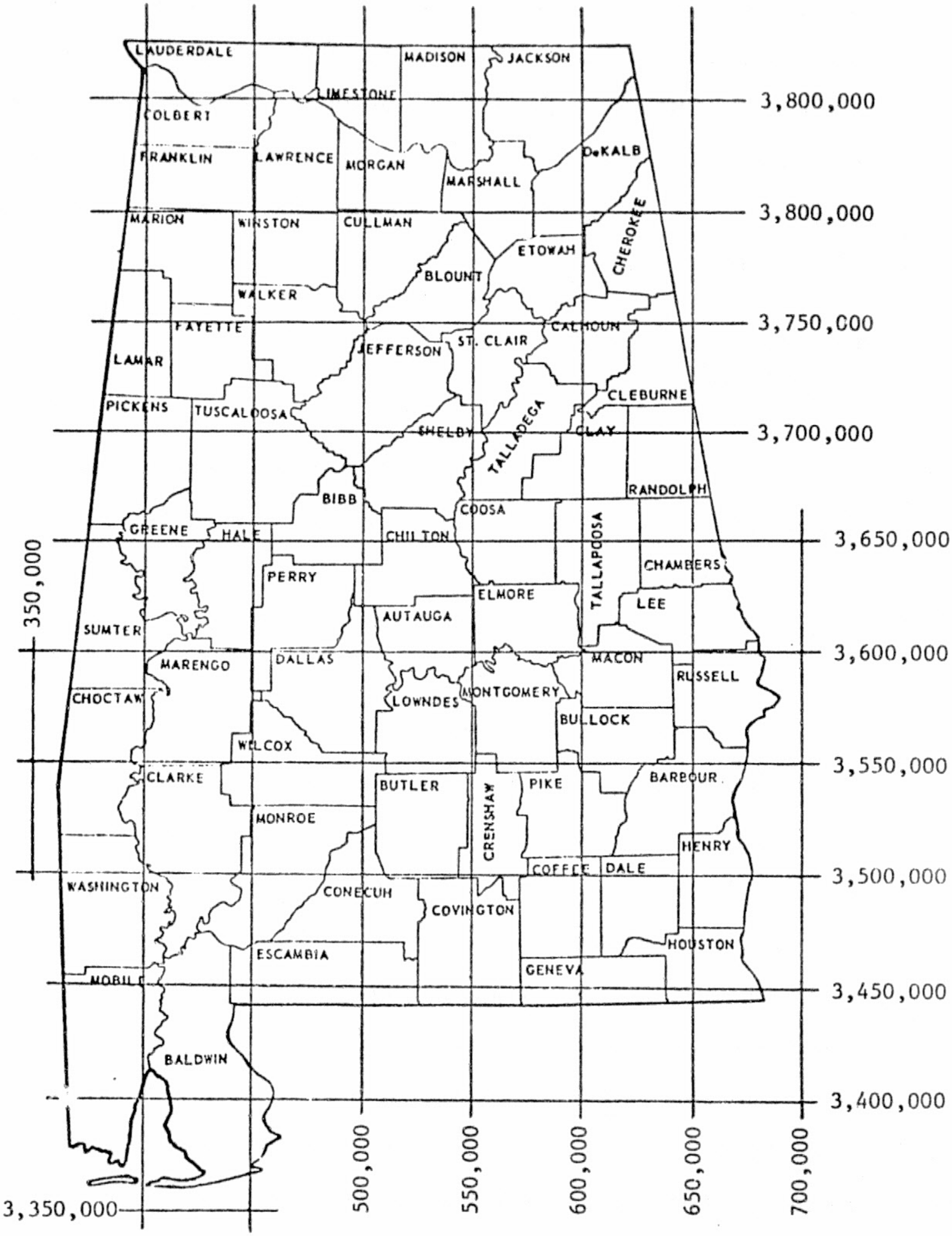

Figure 23. Universal Tranverse Mercator Grid.
UTM Zone 16
50,000 Meter Squares

resolution of about 300 feet restricted the size of a workable cell to not less than one square kilometer. Therefore, to facilitate comparison with the historic data and to maintain consistency, a cell size representing one square kilometer (one square millimeter on the 9.5 inch image) was used. At one square kilometer, the entire State of Alabama contains 135,289 cells.

3.4 The Role of Ground Truth and Other Supplementary Information

Ground truth refers to a collection of ground measurements and observations about the type, size, condition, and any other charateristics of importance concerning the materials on the earth's surface being remotely sensed.[33] Ground truth and other supplementary information were used in this study as described below.

In the acquisition of historic land-use data from U.S.D.A. air photo mosaics, supplementary information was obtained from Alabama county highway maps, U.S.G.S. topographic maps, geologic maps, and land-use maps of the area under study, as well as from ground truth obtained from visits to the area. All of these helped to determine percentages of various land uses contained in each square kilometer. Supplementary information was essential in establishing this relatively accurate historic data base with which to compare land-use data derived from ERTS-I.

In analyzing ERTS-I data supplemental information consisted of the sources mentioned above including the air photo mosaics, but was necessarily restricted to the location and registration of the grid overlay because of limitations imposed by time and the scope of this study.

Transparent line maps of Alabama at the same scale as the ERTS images were used to verify the registration. Furthermore, by not prejudicing the analyst's decision by using extensive supplemental information to determine the type of land use being coded, the first step toward testing the feasibility of mapping land use from ERTS imagery using a minimum of ground truth could be initiated. Subsequent studies hopefully will compare the ERTS-derived land-use information from this study to accurate ground truth of the area to establish confidence limits for ERTS land-use data. Establishing this confidence through statistical comparisons and analyses will facilitate mapping land use directly off of ERTS imagery with a minimum use of ground truth. Until the accuracy of land-use interpretations from ERTS-I imagery can be determined, it should be recognized that comparisons of ERTS-derived land-use data to the historic data base may falsely indicate some apparent changes which may not have been changes at all.

3.5 Extraction of Historic Land-Use Data

3.5.1 Techniques

The historic data for this study were taken from standard black-and-white U. S. Department of Agriculture air photo mosaics, an example of which is given in Figure 24. Mosaics for the nineteen counties in the target study area dated from March, 1964, to January, 1969 (Figure 25), and were at a scale of 1:63,360 or one inch to one mile.

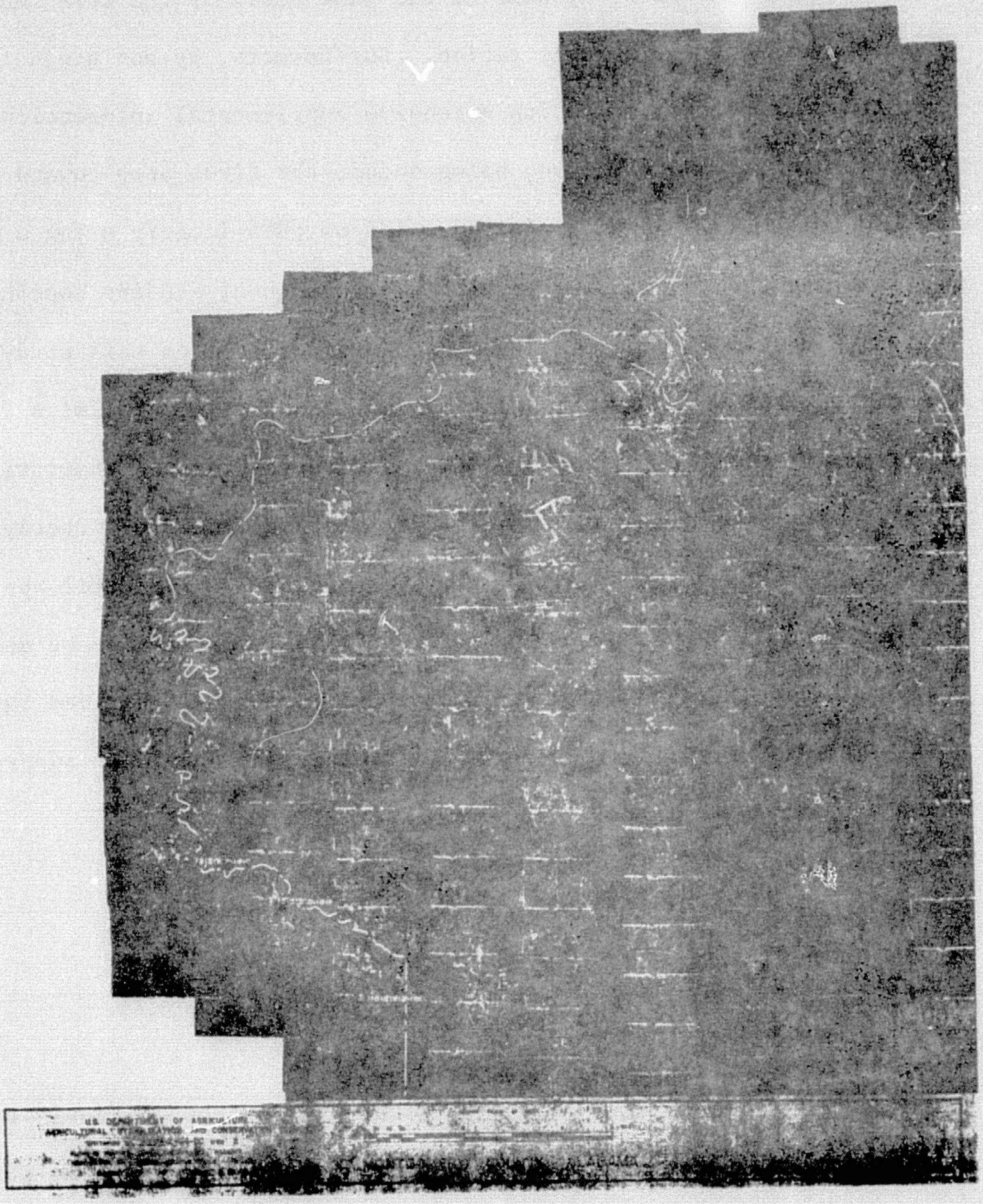

Figure 24. A Sample of the U.S.D.A. Air Photo Mosaic Used in Compiling the Historic Land-Use Data.

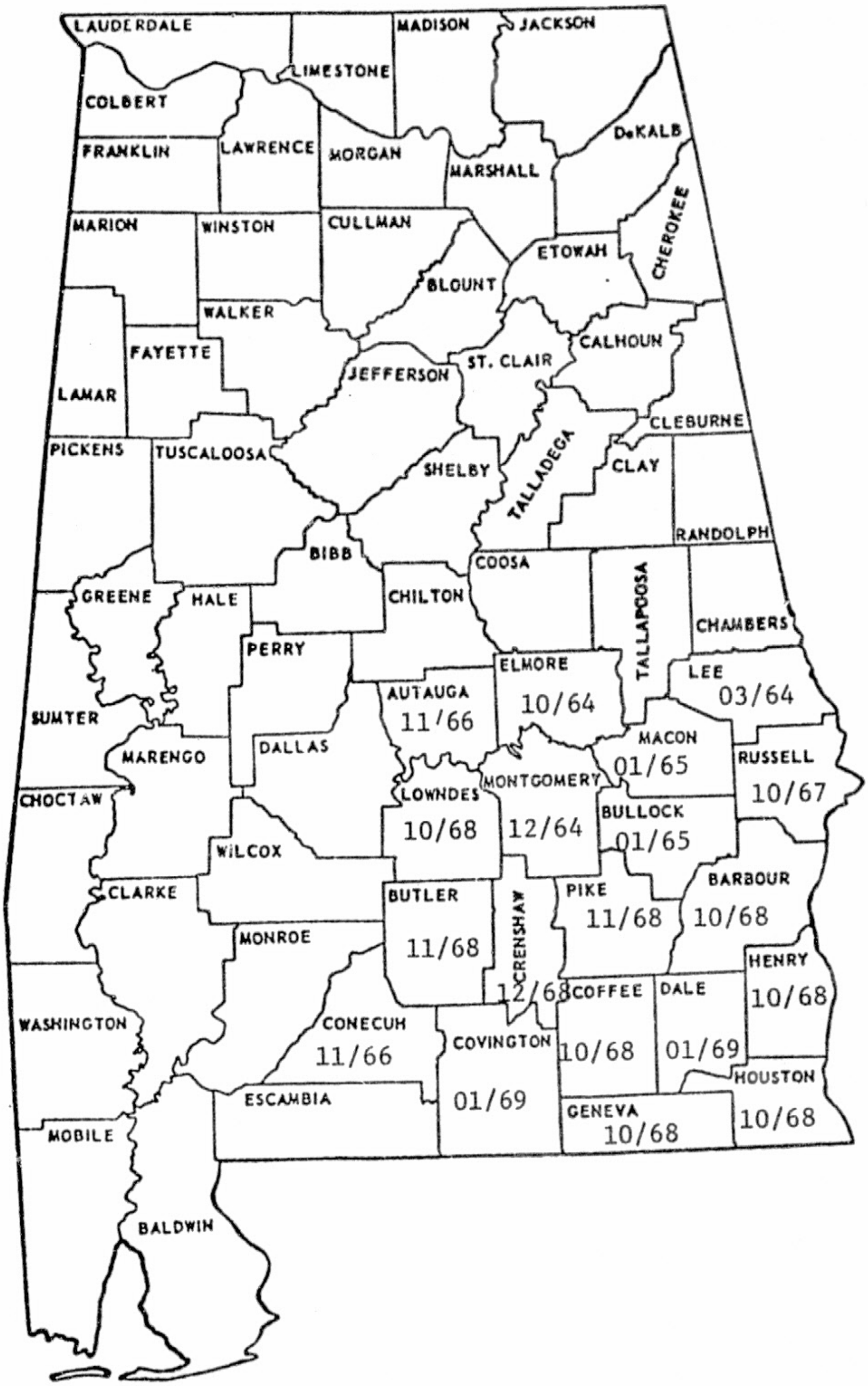

Figure 25. Dates of Airphoto Mosaics, from Which Historic Data Base was Obtained.

Land-Use information was recorded by pencil onto transparent grid overlays (Figure 26) prepared at the Marshall Space Flight Center. The grid cells each represented one square kilometer on the ground and measured 15.8 millimeters square thus corresponding to the scale of the air photo mosaics.

Several preparatory steps had to be taken prior to actual land use coding. First of all, it was necessary to transfer the UTM grid system from U.S.G.S. topographic maps at a scale of 1:250,000 to the one inch to a mile county highway maps. This was accomplished by measuring the distance between parallels and meridians of the Alabama state plane coordinate system and UTM system on the U.S.G.S. maps and then measuring off these same distances from the Alabama state plane coordinate system on the county highway maps employing a scale conversion factor of 1:3.94.

The next step involved positioning the transparent grid overlay on the county highway maps so as to be aligned with the UTM parallels and meridians previously plotted on the map. The grid was then labeled accordingly. When properly aligned, prominent road junctions, river meanders, and other features, along with county borders, were outlined on the grid. The grid was then transferred from the county highway map to the air photo mosaic. The outlines on the grid overlay of features extracted from the county highway map were aligned with those same features contained in the air photo mosaic. In this manner, the UTM system and grid were correctly positioned on the mosaic.

A total of twelve numerical digits were penciled into each 15.8 millimeter square cell. Referring to Figure 27, the first digit in each

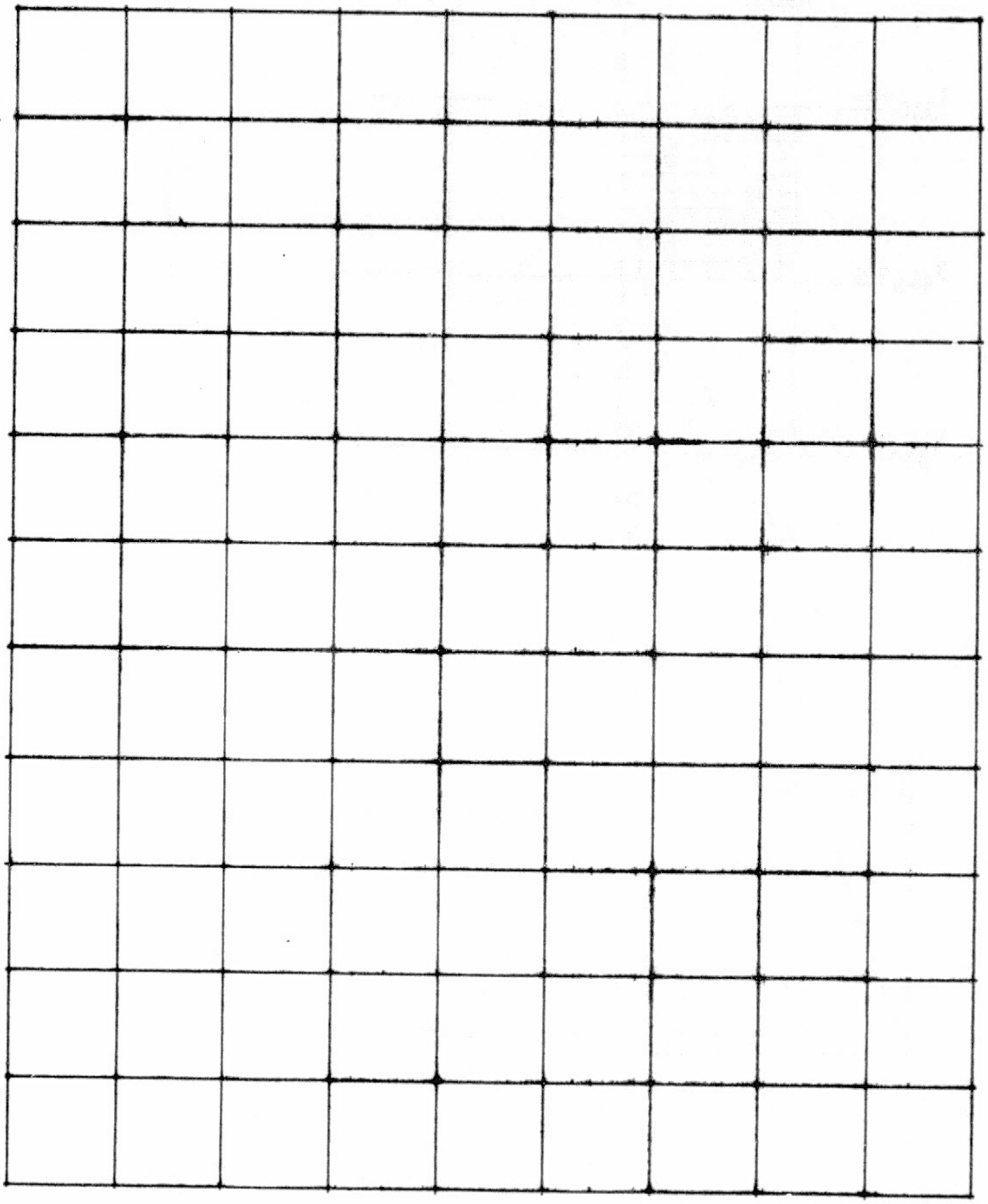

Figure 26. Sample of the Mylar Grid Used in Gathering Historic Land-Use Information.

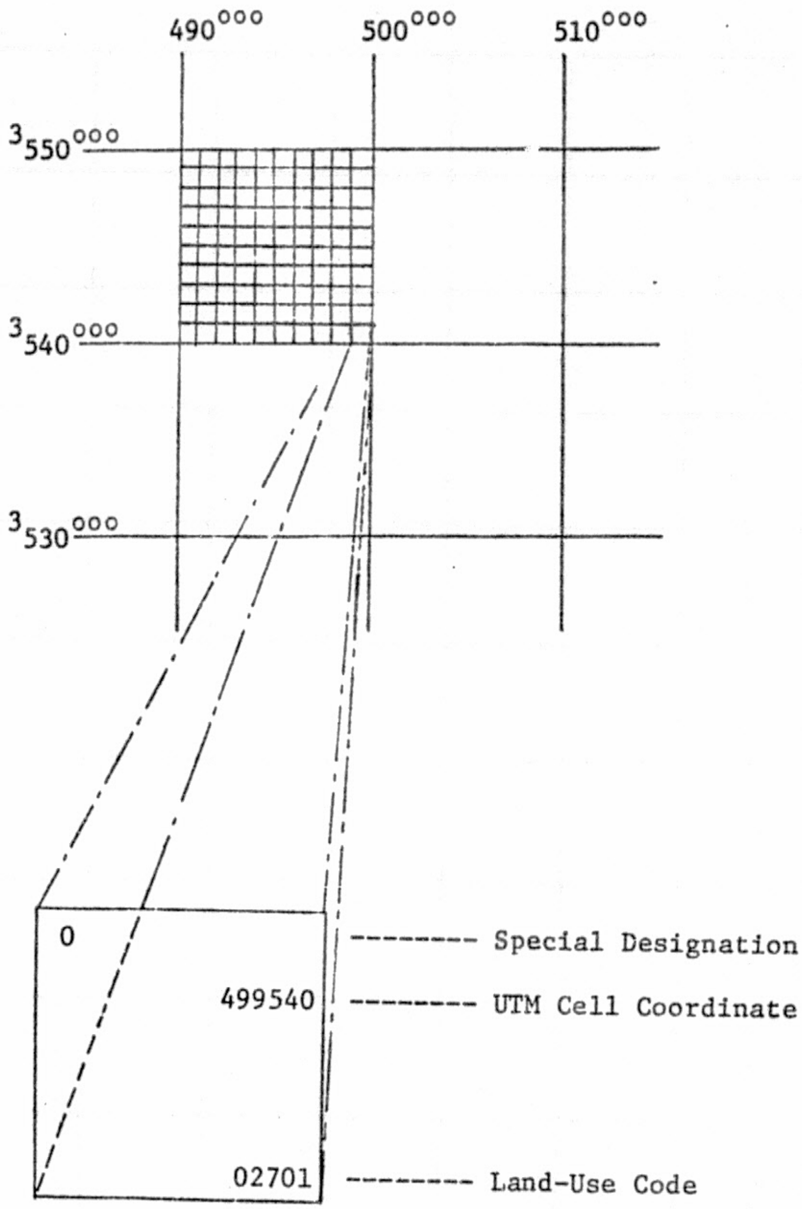

Figure 27. Scheme of Coding Historic Land Use.

cell was placed in the upper left-hand corner and indicated an outstanding feature of particular interest. If there were none, a zero was recorded in that position. For example, every cell containing any part of a particular town may have been given the number "1," and any cell containing any part of a navigable stream in the same county as the town may have been given the number "2," etc. A cell containing both the city and the river would have been given the number corresponding to the city. This code was different for each county depending on the number of towns over 2500 population according to the 1970 U. S. Census and the number of large lakes and navigable streams.

The next six digits recorded referred to the location of the lower left-hand corner of the cell according to the UTM grid system. The first three digits refer to the meridian and the last three to the parallel comprising the left-hand and bottom sides of the cell, respectively. The reader should note that in recording the UTM cell coordinate, an abbreviated form was used. For example, the vertical line (meridian or easting) listed in Figure 27 as 500,000 is abbreviated in the cell to 500. Likewise, the horizontal line (parallel or northing) listed as 3,540,000, indicated that the parallel was 3,540,000 meters north of the equator; and appeared in the cell as 540, since the first digit "3" is constant through the entire length of the State.

The last five digits at the bottom of the cell indicate the percentages of each land use contained within the cell. The numbers were given in the same order of land-use categories as follows: urban, agricultural, forestland, water, and barren land. A sixth digit representing nonforested wetland was recorded when necessary. Each digit

represented tens of percent of one square kilometer occupied by each land use. Hence, the five digits given in Figure 27 indicates that the cell contained zero percent urban land, 20 percent agricultural land, 70 percent forestland, zero percent surface water, and ten percent barren land. 100 percent of any land use per cell was designated by a "+;" therefore, a cell containing nothing but forestland was given the following land-use code: 0 0 + 0 0.

Although it took almost seven months to analyze and record the 1.6 million bits of information for the State of Alabama's 135,389 square kilometers, the methodology utilized makes it the most sophisticated inventory of this magnitude ever attempted in Alabama. In addition, the care with which land-use data was extracted along with the many checks imposed for accuracy and consistency makes it one of the most accurate and useful in existence.

The historic land-use mapping was done in considerable detail relative to the extent to which land uses were evident on the air photo mosaics. The result of this compilation was an accurate but complex data base which served both as a product in itself and as a historic reference with which to compare ERTS-I data.

Two computer mapping programs for pictorial display of the digital data, MIADS and SYMAP, were investigated in detail and ultimately found to be too restrictive in either cell size and scale limitation or lack of combinatorial capability and required computer time, respectively.[34] Therefore, a program was developed by Dr. E. T. Miller of the Department of Civil and Mineral Engineering, The University of Alabama, for analyzing and displaying the land-use inventory data.[35] Through this program, termed ERTSMAP, computer maps were generated which depicted the

percent of a certain land use per cell according to an eleven step density scale. Figures 28 through 32 illustrate in reduced form the type of maps generated for each of the five categories of land use in Montgomery County. Similarly, the program was able to generate maps of dominant land use per cell. A map of dominant land use per cell for Montgomery County is given in Figure 33.

3.5.2 Feature Recognition

At the first level of land-use categories used for compilation of the data, little if any magnification was necessary except in troublesome, extremely complex areas. Accuracy of interpretation was for the most part dependent on the technicians understanding of the classification and, to a lesser degree, a function of the technician's skill and experience in air photo interpretation. Swanson (1969) makes a distinction between "interpretation" and "recognition."[36] Recognition is actually an instantaneous reaction, while interpretation involves more "thought and consideration of the local environment and/or related structures." Not only did technicians have to interpret what was on the ground, but also how much of what was recognized occurred in each cell. It was estimated that between 20 to 30 seconds were required for interpretation, estimation, and recording of the data per cell. Interpretation, of course, was more time consuming when consulting between technicians was necessary.

Tone and texture were the primary considerations in land-use interpretation. Geometric configuration was of lesser importance, but was helpful in distinguishing between nonforested agricultural land and

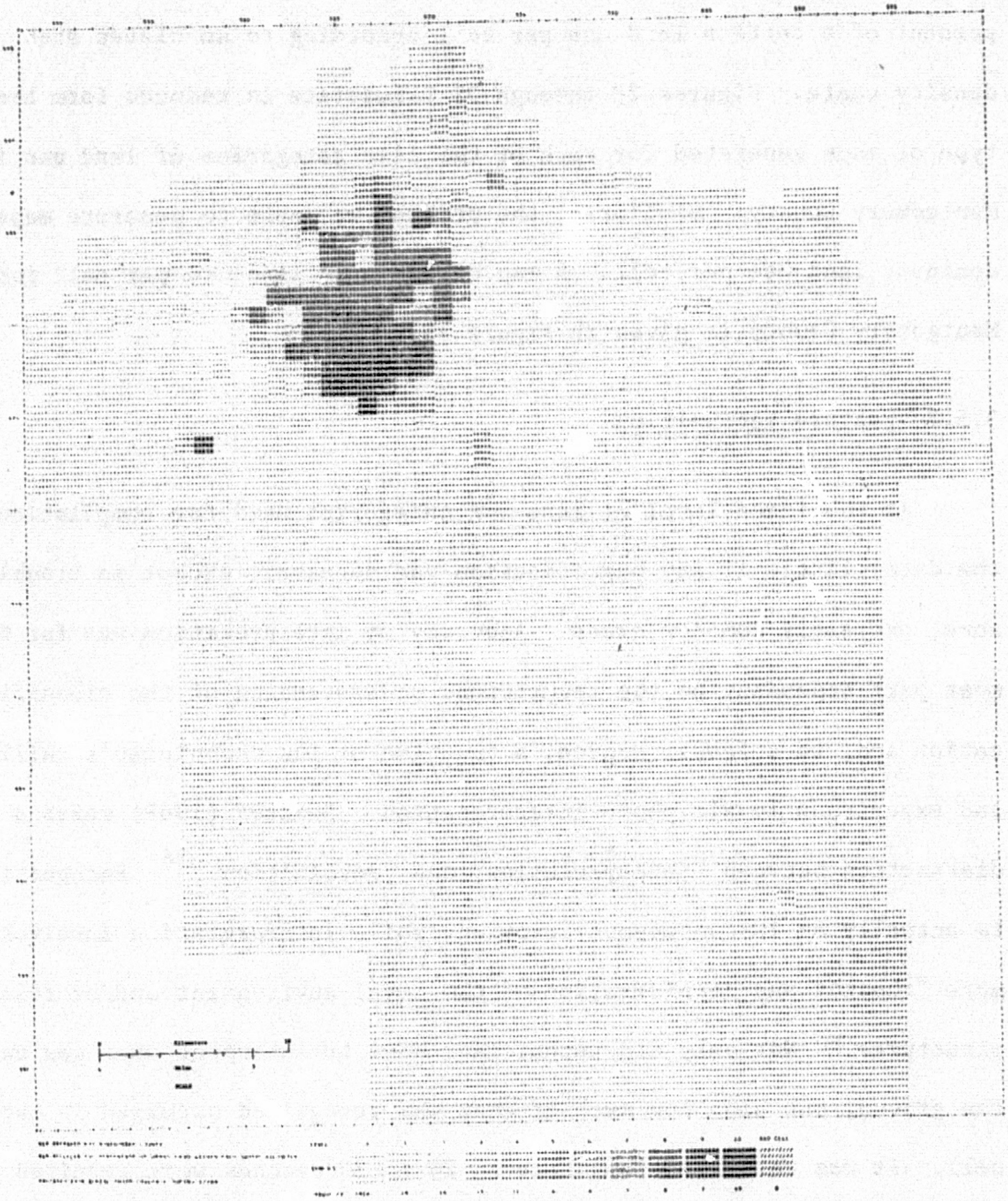

Figure 28. Map Depicting the Percent of Urban Land Per Square Kilometer in Montgomery County.

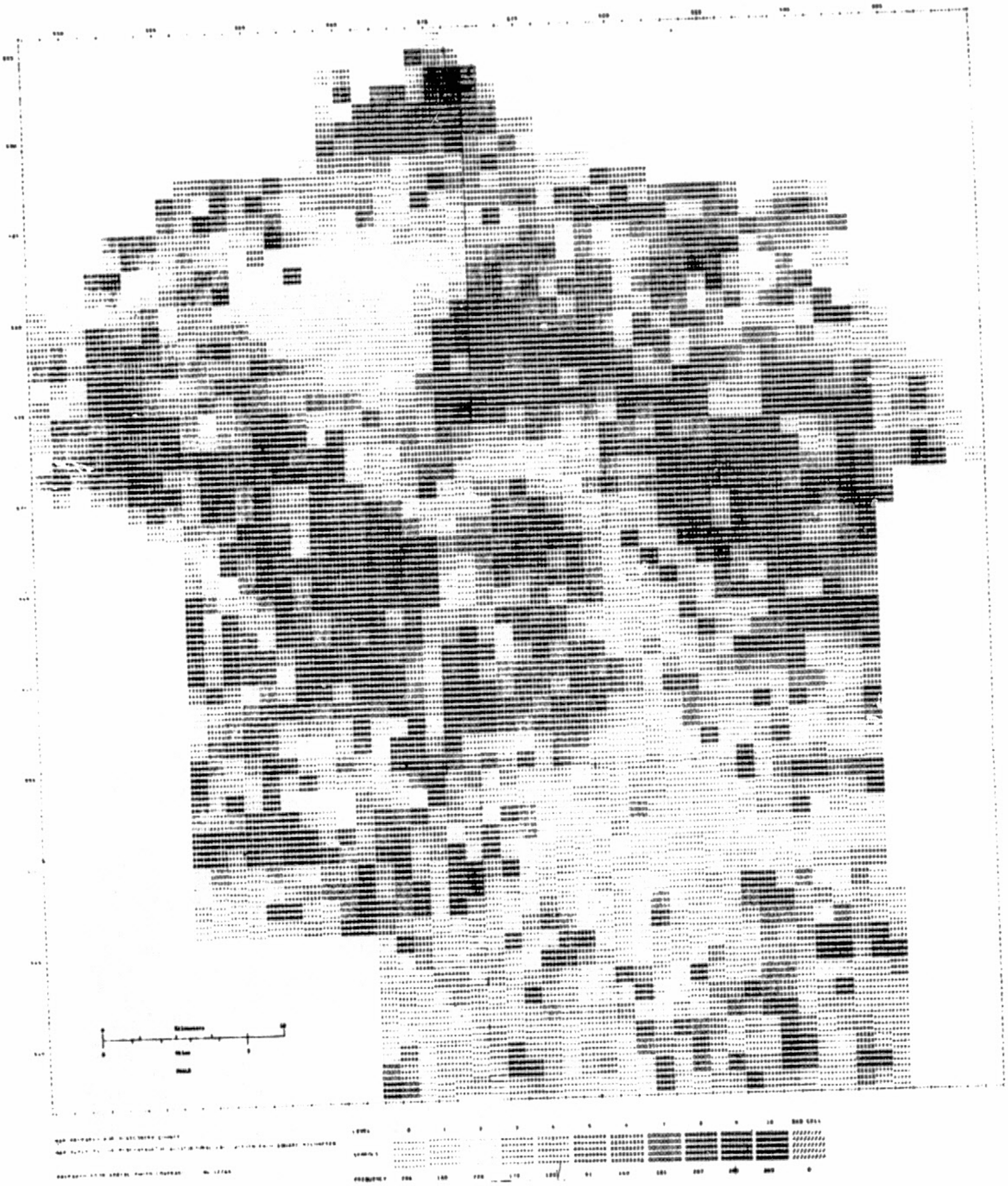

Figure 29. Map Depicting the Percent of Agricultural Land Per Square Kilometer in Montgomery County.

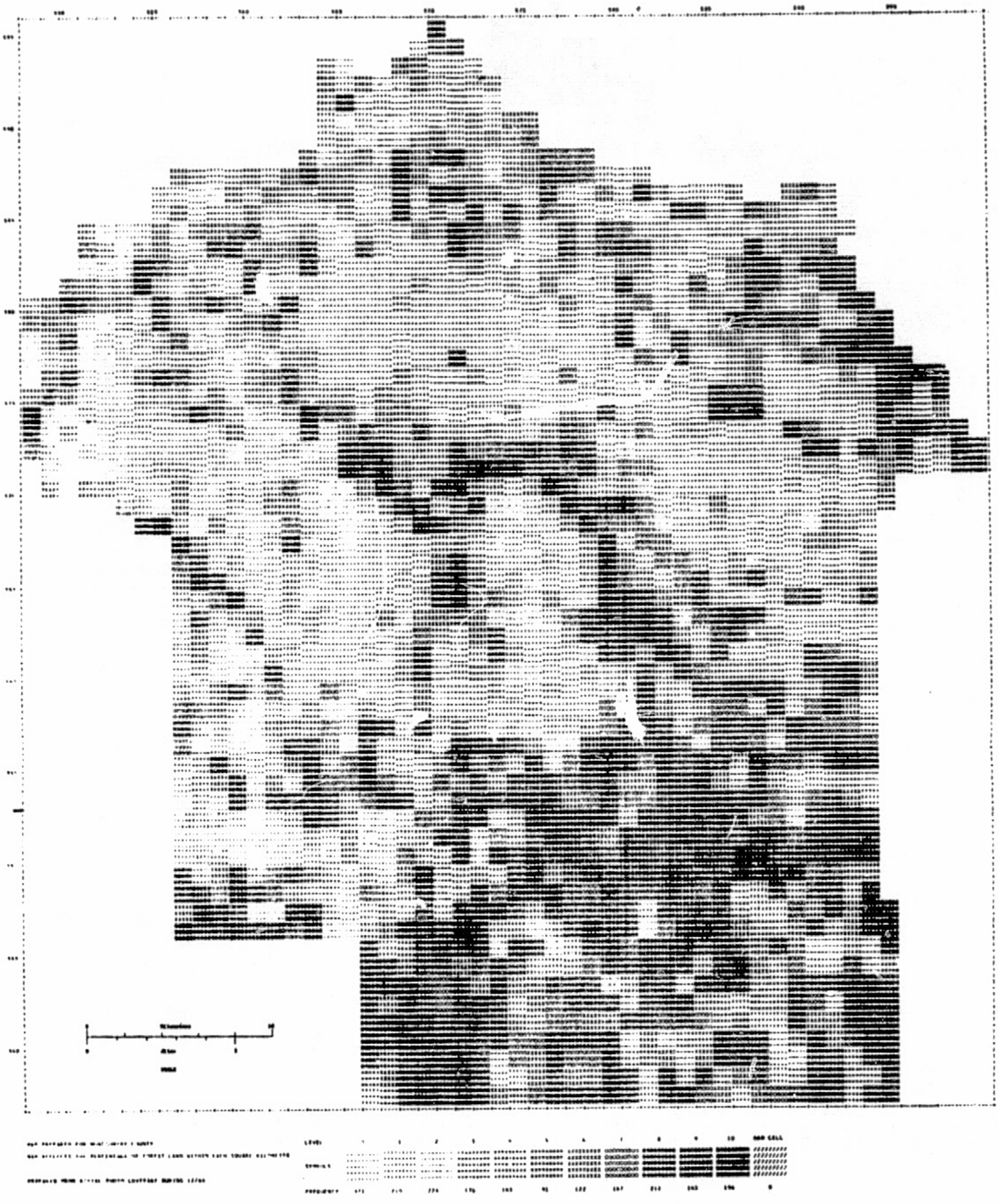

Figure 30. Map Depicting the Percent of Forest Land Per Square Kilometer in Montgomery County.

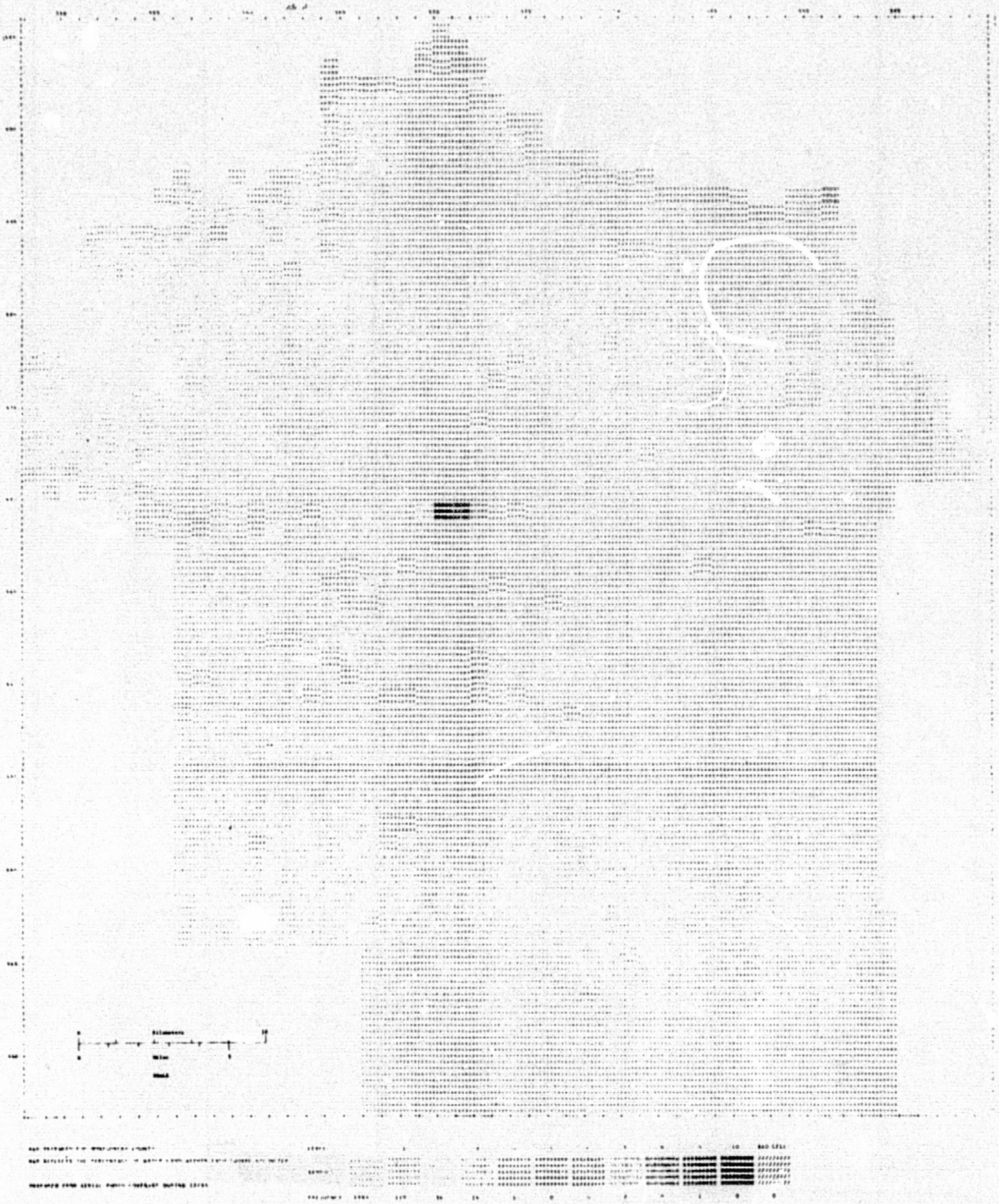

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Figure 31. Map Depicting the Percent of Water Per Square Kilometer in Montgomery County.

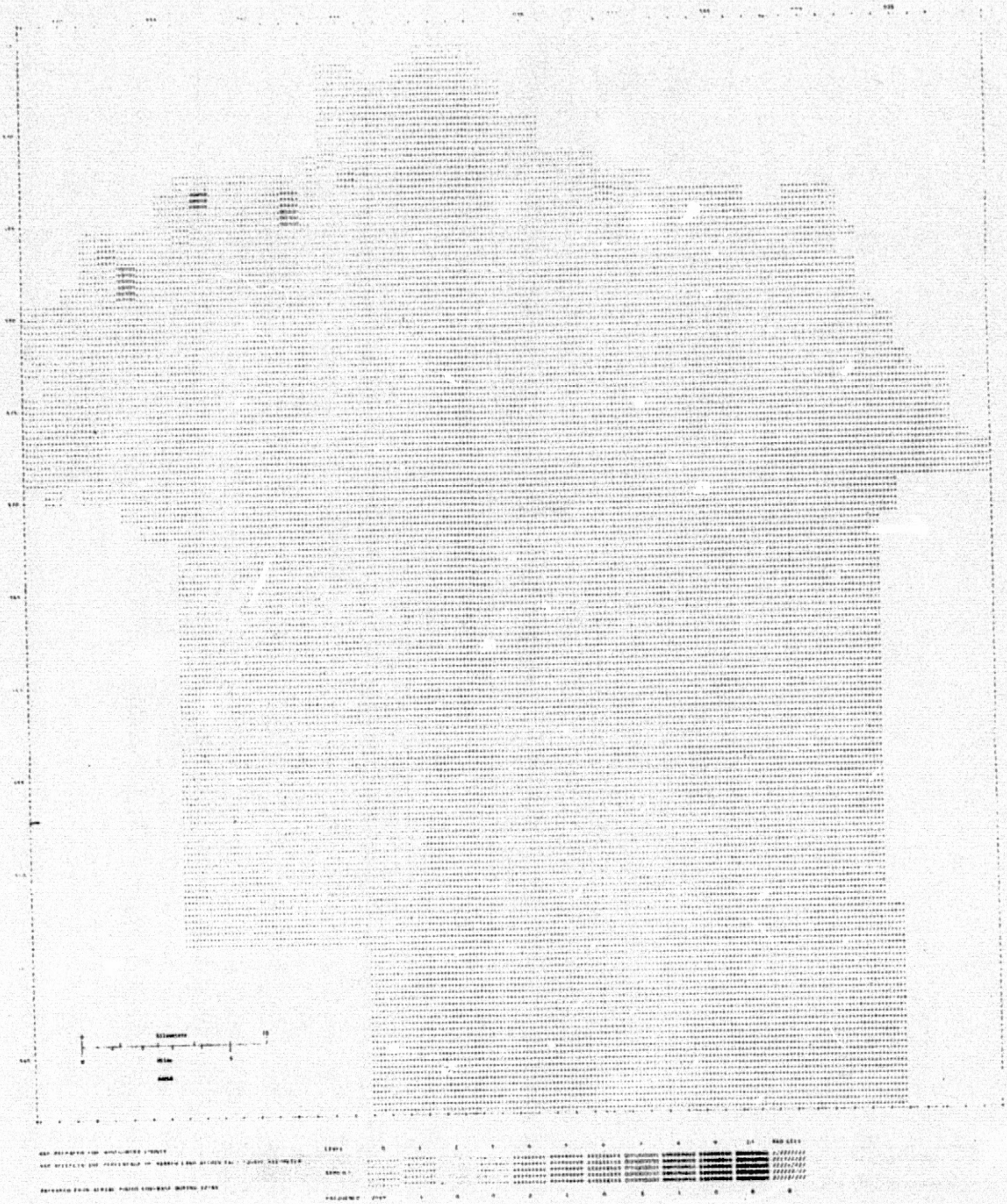

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Figure 32. Map Depicting the Percent of Barren Land Per Square Kilometer in Montgomery County.

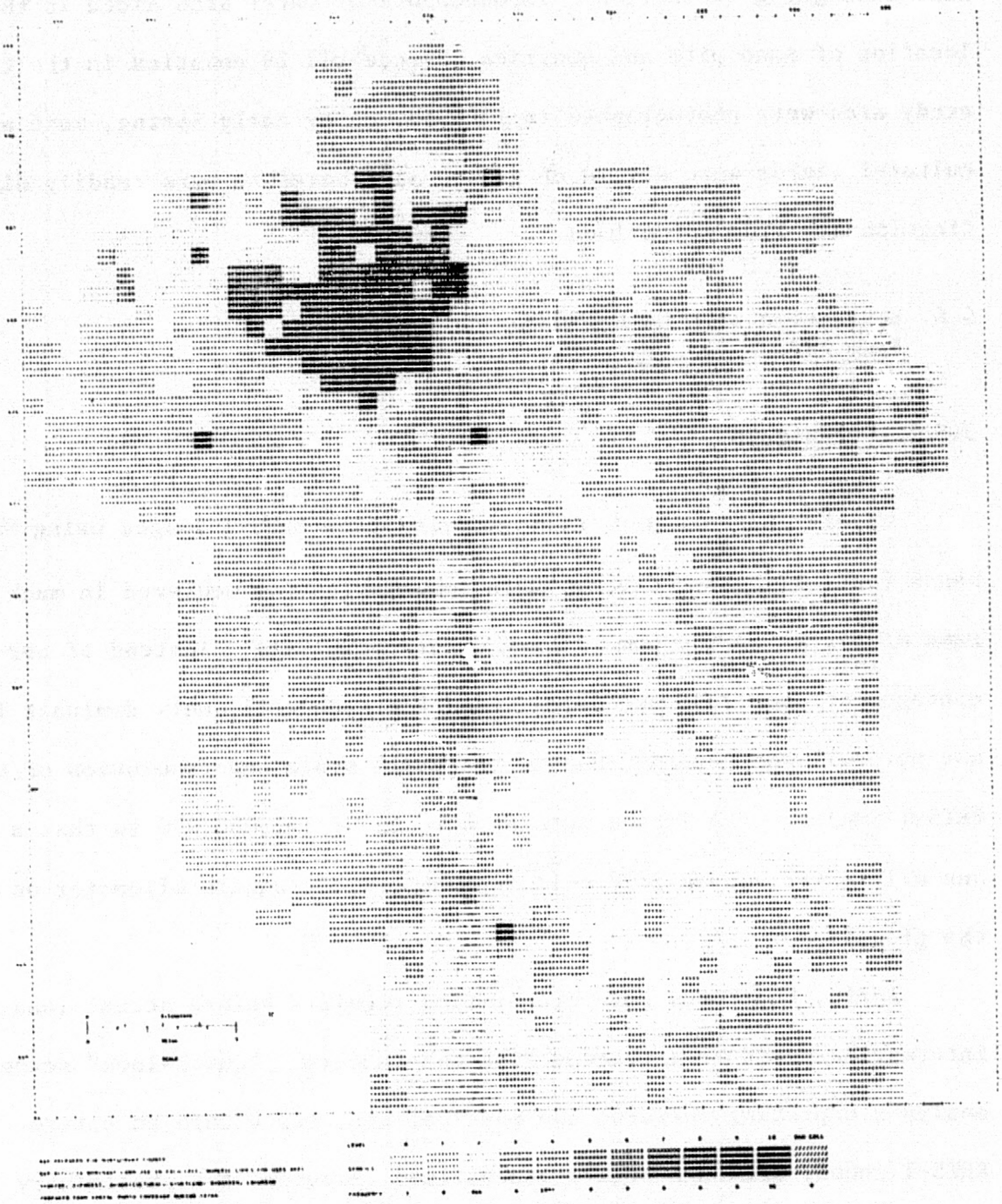

Figure 33. Map Depicting Dominant Land Use Per Square Kilometer in Montgomery County.

land undergoing extraction. Impoundments of water also aided in the location of sand pits and quarries. Since all 19 counties in the target study area were photographed in late Autumn or early Spring, most agricultural fields were devoid of growth and therefore were readily distinguishable from forestland.

3.6 Extraction of Land-Use Data From ERTS-I Imagery

3.6.1 Techniques

Timely land-use data were compiled from ERTS-I images using MSS bands four, five, and seven. Data compilation was achieved in much the same manner as in the compilation of historic data. Instead of percentages of each land use being coded for each cell, only dominant land use per cell was recorded due to the small scale and resolution of the ERTS-I images. The images were at a scale of 1:1,000,000 so that a one millimeter square grid cell represented one square kilometer on the ground.

Again, there was some preparation required before actual land-use information could be extracted from the imagery. "Quick-look" scene analyses depicting cultural and physical features within an entire ERTS-I scene, although highly generalized, provided the preliminary evaluation necessary for more detailed investigation later. Specific problem areas and interesting phenomena were often uncovered and resolved before embarking on a more systematic evaluation. Besides merely indicating possible problems areas, the scene analyses may in themselves provide needed information and insight to planning agencies

and policy makers. Figure 34 (a-c) illustrates the type of product contained in a scene analysis.

Following the preliminary analysis, a more detailed, cell-by-cell land-use inventory was initiated. First of all, an outline map of all 19 counties was prepared on semi-transparent millimeter graph paper using the boundaries established for the historic data base. These county outlines were at the same scale as the ERTS-I imagery facilitating overlay. In this case, however, the grid was placed underneath the ERTS-I positive transparency. The semi-transparent grid served to diffuse light from the light table more evenly and was less grainy than the glass of the light table. In addition, the grid indicated what areas of the image corresponded to the cells in each county.

The next procedure involved positioning the image correctly on the millimeter grid containing the county outlines and labeled according to the UTM system. At least three natural or cultural features were selected from each scene utilized. They were selected on the basis of temporal stability, detectability on ERTS-I imagery, and location relative to each other. Since the UTM coordinates of the cells containing the features were taken from four to seven year old air photo mosaics, features which may have changed location during that time, such as river meanders and strip pits, were unacceptable. The features selected as locational references necessarily had to be clearly defined on the scene to be registered. Finally, the features were chosen so as to form as large a polygon as possible within the scene. Overlapping scenes always had at least one common reference point, thus providing continuity and accuracy. Reference points

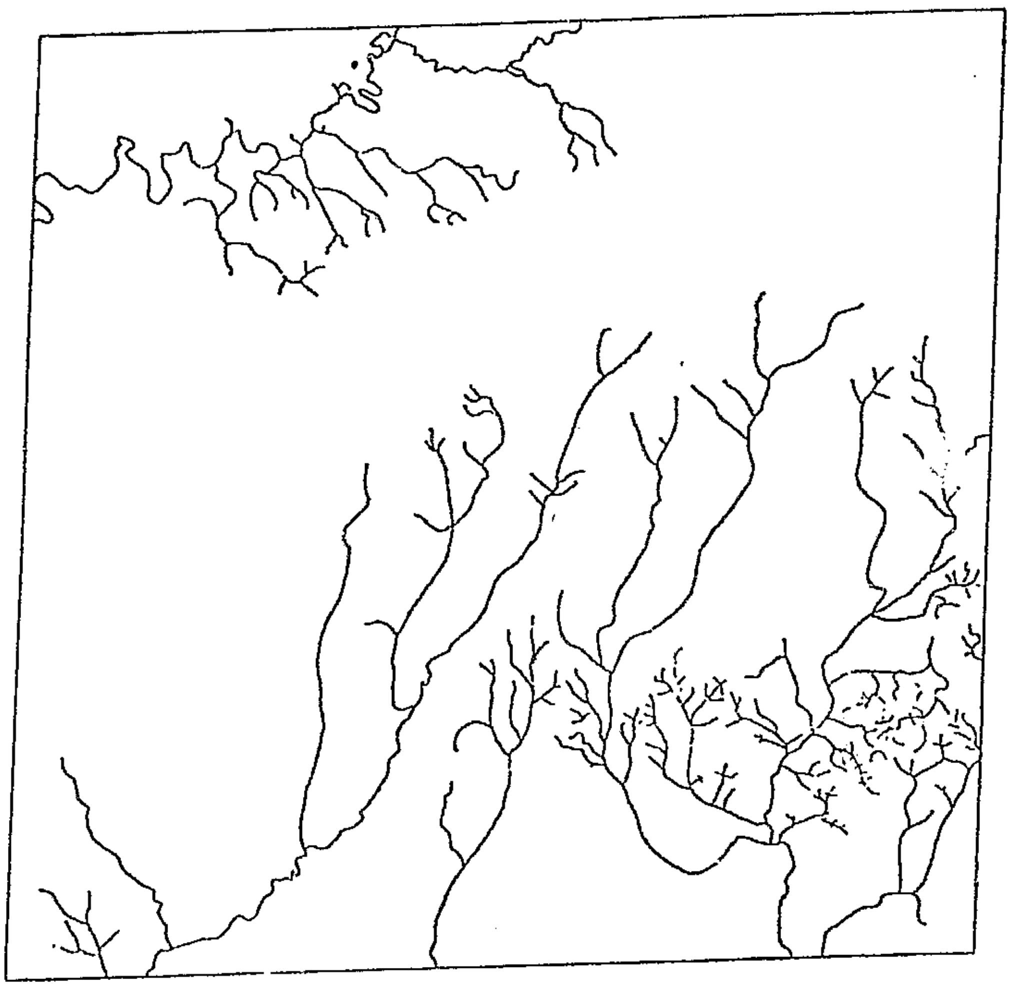

Figure 34a. Map Showing Drainage Patterns as Interpreted from ERTS Frame E-1035-15501.

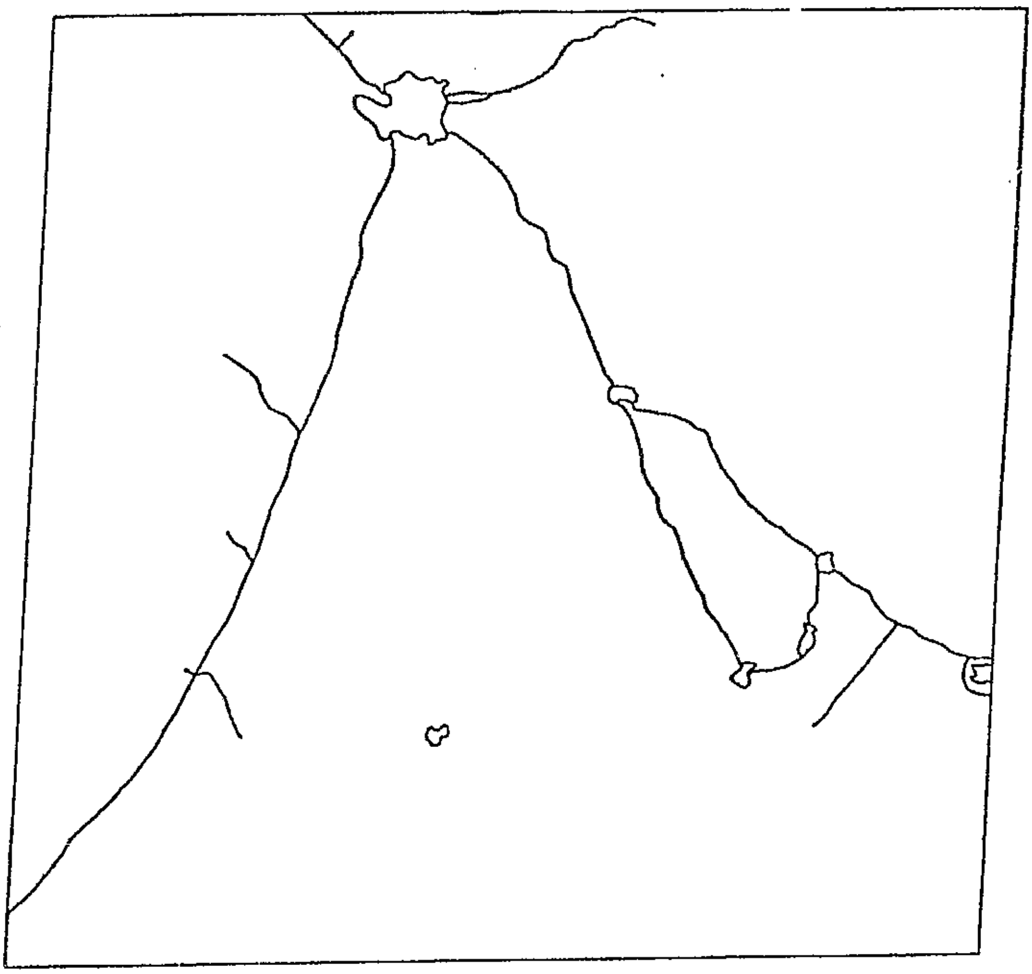

Figure 34b. Map of Transportation Arteries and Urban Areas as Interpreted from ERTS Frame E-1-1085-15501.

1 - Urban

2 - Agriculture

3 - Forest Land

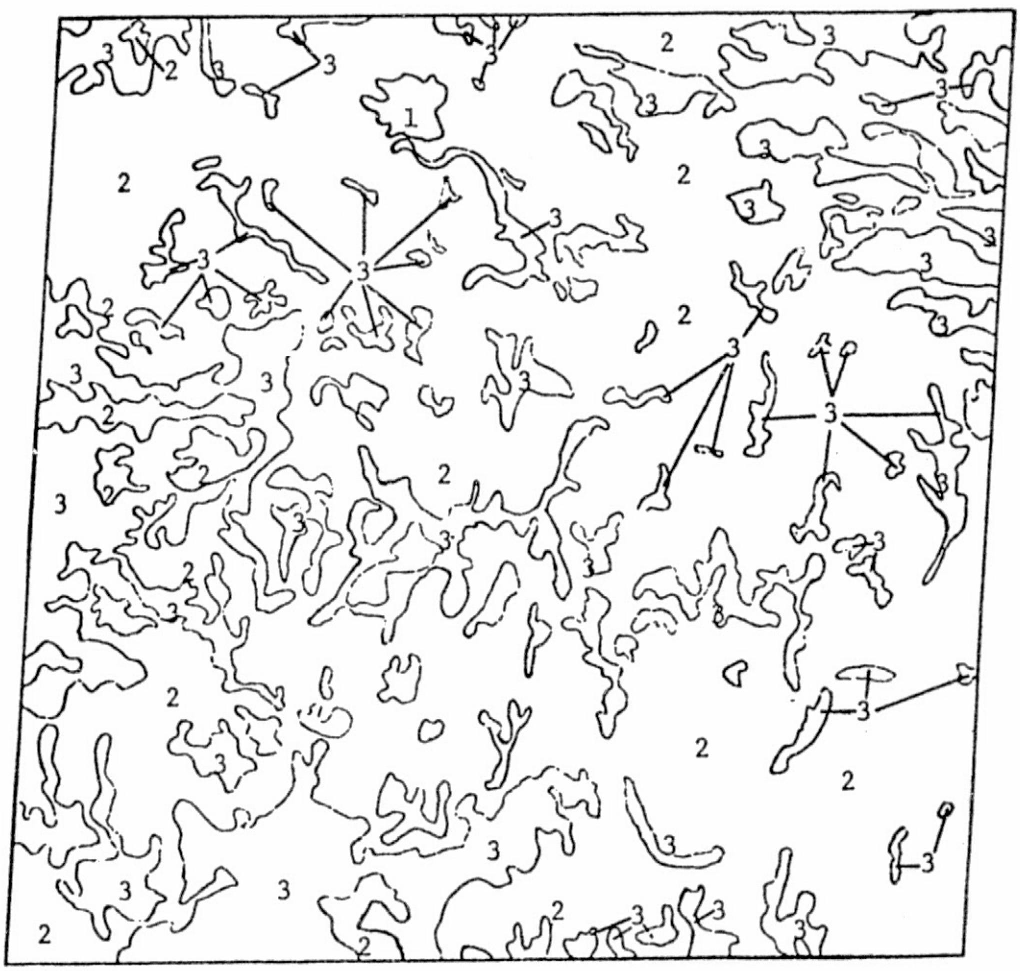

Figure 34c. Land Use as Interpreted from ERTS Frame E-1-1085-15501.

selected included the intersection of two runways at an airport, the confluence of two rivers, small lakes, and dams. Features which could have been used include the intersection of major highways, geologic and geomorphic features, and persistent, stationary, industrial sources of smoke plumes.

After deciding what the locational features would be, their UTM designation was taken from the air photo mosaics. This cell was then outlined on the millimeter grid. It was then a simple matter to align the features in the image with their corresponding cells on the grid. When properly aligned, the center of each registration mark at the four corners of the image was indicated on the grid to facilitate rapid and accurate registration of different spectral bands of the same image without having to repeat the process of feature alignment.

With the county grid and image correctly aligned, a transparent, acetate, "working" grid, at the same scale as the first grid and the image, was placed over the image and aligned with the grid underneath. This point-grid possessed only a dot in each corner of every millimeter square grid cell and therefore did not obliterate any of the detail in the scene itself. Pens especially adapted to writing on acetate were used to indicate significant features and coding progress on the grid overlay.

MSS band seven (0.8 to 1.1 microns) was used to code the cells in each county which were dominated by surface water. This initial step was necessary in order to forego the possibility of erroneously classifying a lake or reservoir as some other form of land use when viewing MSS band four and five (visible bands). After color-coding these

water-dominated cells, the acetate "working grid" was applied to the same scene in band four (spectral green) and band five (spectral red).

Beginning at the top-most left-hand corner of the county, each row of cells was coded from left to right for dominant land use per cell. Using a hand-held 5X magnifier, the dominant land use was determined and communicated to a technician who then recorded that information in the corresponding space on a blank computer printout of that particular county. In this manner, the land-use information for an entire county was recorded in approximately one and one-half hours and in a form ideally suited for subsequent computerization.

After land-use compilation was completed for each county, the data was put into computer format and stored for future comparison with and update of the historic data base. Dominant land-use maps, similar to that contained in Figure 33, were generated from this information.

3.6.2 Feature Recognition

Water features were best delineated on the two infrared bands, MSS six and MSS seven, because of the water's total absorption of electromagnetic energy in that portion of the spectrum (700 to 1100 nanometers). Due to the small scale of the imagery, small rivers were barely visible and could only be inferred from land-use patterns. Small ponds, often less than 100 meters wide, were visible on band seven however.

MSS five (spectral red) was of great value in the recognition and delineation of certain cultural features because of its high contrast ratio. Urban areas, visible as pale gray tones, were evident,

although care had to be taken not to confuse the urban fringe with agricultural land. Where the city was surrounded by darker-toned forest land, the urban-rural interface was readily apparent. Interstate highways as well as some secondary roads were clearly distinguishable. By following these transportation routes, it was possible to locate other urban areas not immediately evident.

Although most of the land-use information was extracted from MSS five, no single MSS band was sufficient in itself. Therefore, supplemental information in the form of 1:250,000 U.S.G.S. topographic maps and 1:63,360 county highway maps was employed. This information was used only to verify the location of a town already coded and was not used to locate urban developments prior to the coding process. Furthermore, whenever ground truth negated the existence of a town in a cell which had been coded as urban, the urban classification was retained. By not "doctoring" the land-use data from ERTS-I in such a manner, a more realistic evaluation of ERTS's potential was obtained.

CHANGE DETECTION

4.1 Comparison of Historic to ERTS-I Land-Use Data Bases

4.1.1 Historic Data Base

The historic land-use information was compiled according to the procedure previously given in Section 3.5.1. To facilitate comparison of this data to land-use data acquired from ERTS-I, it was necessary to modify the mapping algorithm to produce maps portraying dominant land use per square kilometer. For example, a cell originally containing 10 percent urban, 40 percent agricultural, and fifty percent forestland would be represented on the dominant land-use map simply as forestland.

As can be seen from Table III, most of the cells in each county contained no more than two land use categories. In a few of the cells containing two or more categories, the dominance was shared by two categories, e.g., a cell containing 50 percent urban and 50 percent agricultural land. When this occurred, a "tie-breaker" was included in the mapping program to assign priorities to the six classes of land use. The order of preference was offered by officials of the Alabama Development Office to correspond to the cell's potential for urbanization. The order of preference is as follows: urban, barren land, wetland, agricultural, forest, and water. In other words, a cell in which barren land

TABLE III

The Number of Cells (in Percent) Containing a Certain Number of Land-Use Categories

County	Number of Land-Use Categories Per Cell					
	1	2	3	4	5	6
Conecuh	30.88	68.27	0.85	0.00	0.00	0.00
Covington	34.74	65.53	1.64	0.07	0.00	0.00
Crenshaw	28.36	70.82	0.82	0.00	0.00	0.00
Dale	15.04	81.97	2.99	0.00	0.00	0.00
Elmore	25.90	66.21	7.42	0.48	0.00	0.00
Autauga	19.71	74.35	5.81	0.12	0.00	0.00
Barbour	22.02	74.16	3.22	0.59	0.00	0.00
Bullock	15.79	83.35	0.86	0.00	0.00	0.00
Butler	26.95	71.32	1.74	0.00	0.00	0.00
Geneva	8.82	86.76	4.28	0.13	0.00	0.00
Henry	19.19	77.73	3.01	0.06	0.00	0.00
Houston	14.01	81.71	4.28	0.00	0.00	0.00
Lee	26.87	69.70	3.30	0.12	0.00	0.00
Lowndes	21.10	76.10	2.83	0.05	0.00	0.00
Macon	22.70	74.33	2.90	0.06	0.00	0.00
Montgomery	24.90	66.81	8.09	0.19	0.00	0.00
Pike	10.47	87.13	2.40	0.00	0.00	0.00
Russell	23.57	71.86	4.20	0.36	0.00	0.00
Coffee	18.30	79.75	1.95	0.00	0.00	0.00

and forest share the dominance, the cell would appear simply as barren land on the map of dominant land use.

Although the dominant land-use maps facilitate comparison with ERTS-I data, care must be exercised in their interpretation. For example, a small community may occupy a portion of four cells but dominate none and, therefore, not be displayed on a dominant land-use map. Likewise, a cell may contain three different land-use types where none of the three constitute even fifty percent of the cell (e.g., 30 percent urban, 30 percent agricultural, 40 percent forestland), but because forestland is the dominant land use in the cell, although not even half the area, the cell appears as totally forest on the dominant land-use map.

From Table IV it can be seen that most of the counties are predominantly forestland in a forest to agriculture ratio of roughly two to one. Geneva and Houston counties reverse this relationship and are mostly agricultural by a ratio of two to one over forestland. Montgomery County contains only slightly more agricultural land than forestland. Urban areas constitute just slightly more than one percent of the area according to the historic data. Of course, this reflects only those communities which dominate one square kilometer or more on the grid; hence, many smaller communities were not represented.

Notice that in Table IV, the seventh column applies to "bad cells." This is somewhat of a misnomer in that, in most cases, "bad cells" were intentionally coded as such to provide a means of identifying military installations and reserves. Indeed, the occurrence of only a few randomly spaced "bad cells" indicate what the name implies, that is, the

TABLE IV

The Distribution (in Percent) of Land Use Types in Each County According to the Historic Data Base and Using Dominant Land Use in Each Cell

County	Urban	Agri.	Forest	Water	Barren	Wetland	Bad
Autauga	0.63	24.19	74.86	0.32	0.00	0.00	0.00
Barbour	0.64	30.20	67.55	1.36	0.21	0.00	0.04
Bullock	0.24	43.15	56.61	0.00	0.00	0.00	0.00
Butler	0.50	17.86	81.19	0.15	0.00	0.25	0.05
Coffee	1.15	39.35	59.50	0.00	0.00	0.00	0.00
Conecuh	0.24	13.09	86.67	0.00	0.00	0.00	0.00
Covington	0.70	27.94	71.07	0.29	0.00	0.00	0.00
Crenshaw	0.19	23.02	76.79	0.00	0.00	0.00	0.00
Dale	0.79	29.94	58.07	0.00	0.00	0.00	11.20
Elmore	0.90	29.96	65.07	4.07	0.00	0.00	0.00
Geneva	0.71	66.78	32.38	0.00	0.00	0.13	0.00
Henry	0.46	41.13	56.97	1.44	0.00	0.00	0.00
Houston	3.18	65.50	30.35	0.32	0.00	0.00	0.65
Lee	2.25	23.50	73.13	1.06	0.00	0.00	0.06
Lowndes	0.16	43.06	55.60	0.00	0.00	0.00	1.18
Macon	0.86	38.47	60.67	0.00	0.00	0.00	0.00
Montgomery	4.43	53.10	42.04	0.14	0.29	0.00	0.00
Pike	0.94	39.65	59.36	0.00	0.00	0.00	0.05
Russell	2.01	28.46	66.29	1.59	0.06	0.00	1.59

presence of an anomaly in either coding or key-punching. The presence of an agglomeration of "bad cells" in any one area, however, always indicates the presence of a military installation. Examples of this are in Russell County (27 bad cells corresponding to Fort Benning Military Reservation) and in Dale County (156 bad cells corresponding to Fort Rucker). A more appropriate title for these cells, rather than "bad cells," would be the term "other," denoting a cell dominated by a land use other than the standard six classifications.

4.1.2 ERTS-I Data Base

The compilation of land-use information from ERTS-I imagery was previously described in Section 2.6.1. This dominant land use per square kilometer was computerized and entered into the data file to allow internal correlation and comparison of data acquired by ERTS-I with the historic data discussed in the previous section.

Table V contains the results of the land-use survey from ERTS-I imagery. As in Table IV, this survey indicates that forestland is still the dominant land use in most of the counties. Unlike Table IV, however, no barren or wetland was recorded in Table V.

"Bad cells" in Table V indicate card-punch or computer printout errors and not military reserves as in the historic data base. Military bases appeared as urban or forest areas on ERTS-I imagery and were coded as such which accounts for the relatively low percentage of "bad cells" in Table V. Accordingly, the coding of forestland inside the bounds of a military reserve previously coded as "bad cells" would account for an apparent increase in forestland in a county when in actuality, the total

TABLE V

The Distribution (in Percent) of Land Use Types
in Each County According to ERTS-I Data

County	Urban	Agri.	Forest	Water	Barren	Wetland	Bad
Autauga	1.70	37.40	59.13	1.77	0.00	0.00	0.00
Barbour	3.22	36.51	59.13	1.69	0.00	0.00	2.16
Bullock	1.65	35.01	62.42	0.00	0.00	0.00	0.92
Butler	1.69	25.21	70.97	0.00	0.00	0.00	2.13
Coffee	1.78	40.39	57.83	0.00	0.00	0.00	0.00
Conecuh	1.27	23.59	75.14	0.00	0.00	0.00	0.00
Covington	1.13	29.63	68.84	0.40	0.00	0.00	0.00
Crenshaw	2.58	40.25	57.17	0.00	0.00	0.00	0.00
Dale	3.73	32.95	63.03	0.29	0.00	0.00	0.00
Elmore	4.13	39.59	50.96	5.32	0.00	0.00	0.00
Geneva	2.79	54.25	42.96	0.00	0.00	0.00	0.00
Henry	1.89	51.74	44.73	1.64	0.00	0.00	0.00
Houston	7.98	68.68	23.34	0.00	0.00	0.00	0.00
Lee	5.92	23.07	69.01	2.00	0.00	0.00	0.00
Lowndes	1.44	43.48	54.97	0.00	0.00	0.00	0.11
Macon	3.59	40.26	56.15	0.00	0.00	0.00	0.00
Montgomery	9.00	58.30	32.70	0.00	0.00	0.00	0.00
Pike	2.98	54.15	42.69	0.00	0.00	0.00	0.18
Russell	4.96	43.56	51.13	0.35	0.00	0.00	0.00

number of acres in forests may have decreased. Dale County is an excellent example. While most counties increased in agricultural land at the expense of forestland, Dale County increased in both categories as well as in urban. According to ERTS-I imagery, Fort Rucker was not coded as "bad cells" but was coded as urban and forested.

4.2 Results

4.2.1 Regional Change

Table VI illustrates the change in each land-use category as a percent of the total county area. As would be expected, urban land use increased in all nineteen counties. Also to be expected was the spread of agricultural areas at the expense of previously forested land. This was true for sixteen of the nineteen counties in the target study area. Likewise, in most of the counties experiencing agricultural growth, there was a corresponding decrease in forestland. Surface water increased or decreased very little in any of the nineteen counties; and where changes in this category were noted in Table VI, they were probably due to a slight misalignment of the grid during the coding process or a failure to detect the water body on the ERTS-I imagery.

4.2.2 Urban Change

One broad goal of this study was to evaluate the utility of ERTS-I data to problems of land-use management. There is no greater need for management and planning than in the field of urban development. Urban areas are usually the most dynamic of the six primary land use categories and are excellent indicators of the economic and social climate

TABLE VI

The Change of Each Land-Use Type as a
Percent of Total County Area

County	Urban	Agri.	Forest	Water	Barren	Wetland	Bad
Autauga	1.07	13.21	-15.73	1.45	0.00	0.00	0.00
Barbour	2.58	6.31	-11.13	0.33	-0.21	0.00	2.12
Bullock	1.41	- 8.14	5.81	0.00	0.00	0.00	0.92
Butler	1.19	7.35	-10.22	-0.15	0.00	-0.25	2.08
Coffee	0.63	1.04	- 1.67	0.00	0.00	0.00	0.00
Conecuh	1.03	10.50	-11.53	0.00	0.00	0.00	0.00
Covington	0.43	1.69	- 2.23	0.11	0.00	0.00	0.00
Crenshaw	2.39	17.23	-19.62	0.00	0.00	0.00	0.00
Dale	2.94	3.01	4.96	0.29	0.00	0.00	-11.20
Elmore	3.23	9.63	-14.11	1.25	0.00	0.00	0.00
Geneva	2.08	-12.53	10.58	0.00	0.00	-0.13	0.00
Henry	1.43	10.61	- 12.24	0.20	0.00	0.00	0.00
Houston	4.80	3.19	- 7.01	-0.32	0.00	0.00	-0.65
Lee	3.67	- 0.43	- 4.12	0.94	0.00	0.00	-0.06
Lowndes	1.28	0.42	- 0.63	0.00	0.00	0.00	1.07
Macon	2.73	1.79	- 4.52	0.00	0.00	0.00	0.00
Montgomery	4.57	5.20	- 9.34	-0.14	-0.29	0.00	0.00
Pike	2.04	14.50	-16.67	0.00	0.00	0.00	0.13
Russell	2.95	15.10	-15.16	-1.24	-0.06	0.00	-1.59

of the region. It is obvious, therefore, that the continuous monitoring of these urban areas and periodic mapping of their growth would facilitate the resolution of many regional planning problems. Despite the necessity of information concerning the location and extent of cities and towns, however, previous sources of such information represent the results of a variety of ad hoc procedures that have developed over the years. In contrast, ERTS-I provides regional planners with timely and synoptic information concerning the urban expansion within their areas.

Figure 35 is an example of the type of urban change maps that can be generated by comparing ERTS-I data to an accurate historic base map. By putting the urban change maps for all nineteen counties together to form a mosaic such as Figure 35, regional urban growth trends are more likely to become apparent.

Figure 35 indicates that many towns not displayed on the historic dominant land-use maps were evident for the first time according to ERTS-I imagery showing substantial growth of smaller as well as larger urban areas. The causes of this urban growth and its resulting growth trends will be discussed further in Section 4.3.

4.2.3 Rural Change

The data in Table VI indicates that the dominant transition to rural land use in the target study area was from forest to agriculture. Bullock, Geneva, and Lee counties, however, experienced a decline in agricultural land with all but Lee County exhibiting a corresponding increase in forestland. In Lee County, the loss of agricultural land was not substantial (less than one percent) and can be attributed to

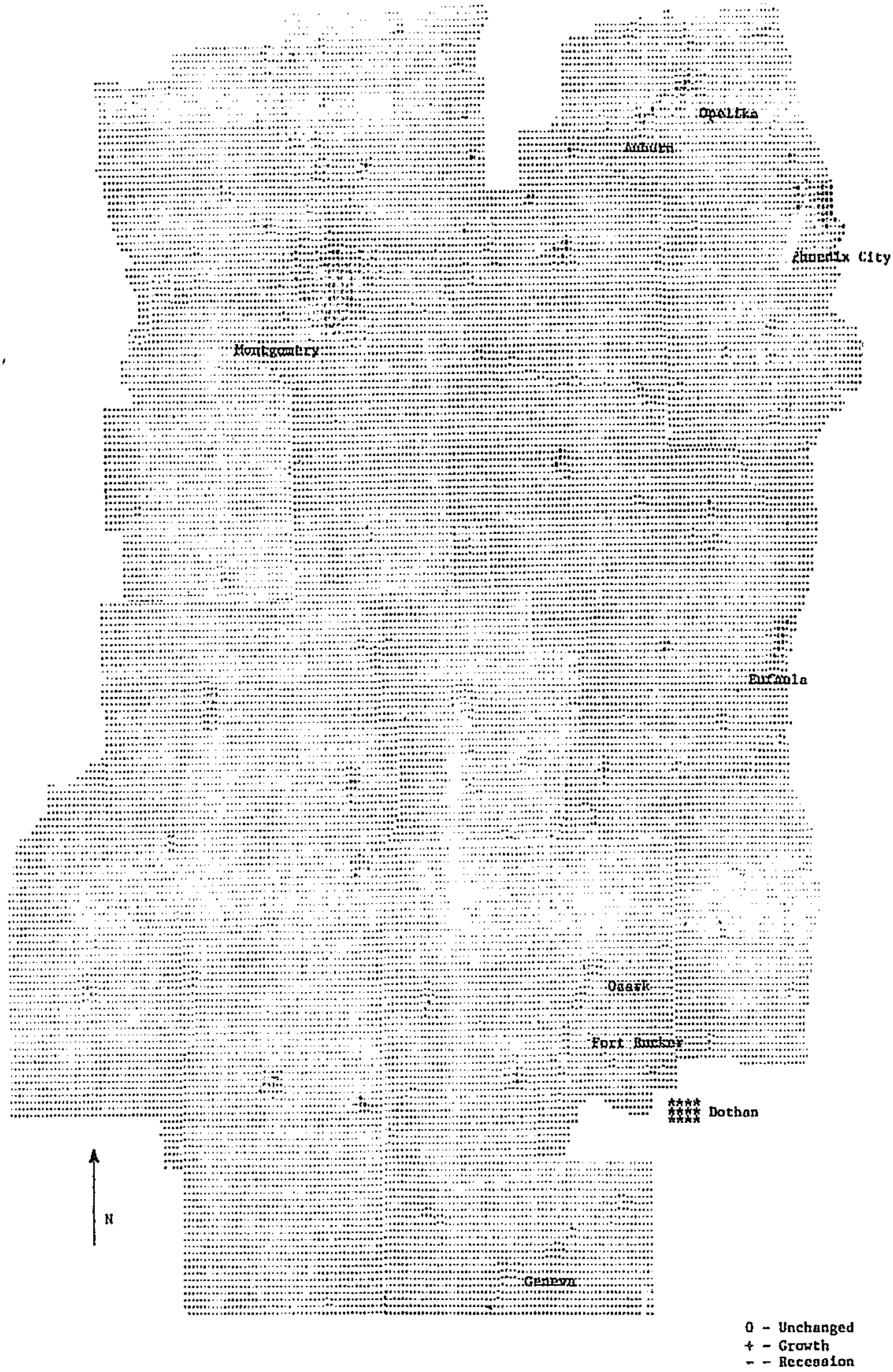

Figure 35. Urban Change Map.

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either an error in coding or the transgression of previously farmed and forested lands by the expanding Auburn-Opelika urban area. The decrease of agricultural activity in Geneva County is partly due to the expanding practice of growing trees for pulp-wood and to errors inherent in the production of dominant land-use maps. For example, in Geneva County, farm fields tend to aggregate between wooded dendritic stream patterns. The areas surrounding even smaller tributaries are often swampy and unsuitable for agricultural activity and are thus wooded. Therefore, most fields are contiguous with forested areas surrounding fingerling streams or larger rivers. These forested areas did not constitute the dominant form of land use in most of the cells in the historic data base, however, and the cells were coded as predominantly agricultural. When using ERTS-I data (dated September, 1972), however, many of the fields still contained vegetation, which, along with the fact that the dark forested areas tended to overshadow and blur the lighter-toned agriculutral fields, accounts for the apparent decrease in cultivated land and an apparent increase in forested land. The situation in Bullock County was somewhat more intriguing and proved to be a valuable lesson in the compilation of land use from low-resolution imagery as well as a commendation of the seasonal coverage afforded by ERTS-I. The apparent decrease in agricultural land and increase in forestland was not so much the result of an error in interpretation, per se, as it was the failure of the MSS sensors aboard ERTS-I to discriminate between growing vegetation in farm fields and natural forest crown cover surrounding them. Inspection of January ERTS-I imagery of the same area indicated that many of the fields, then devoid of vegetation, had been

erroneously coded as forestland using September imagery. This dramatically demonstrated to the writer the great benefits of the seasonal coverage rendered by ERTS-I.

4.3 Trend Detection and Analysis

Figure 36, a representation of the urban information contained in Table VI, illustrates, on a county-by-county basis, the major centers of urban growth in southeastern Alabama. According to Figure 36, Mongomery and Houston counties have exhibited the greatest amount of urban growth over the past nine and five years, respectively, followed closely by Elmore and Lee counties. Macon, Crenshaw, Pike, Barbour, Dale, and Geneva counties were next in line with an urban expansion of between two and three percent of the total county areas.

Some definite regional trends in urban development are evident from Figures 35 and 36. It can be seen that the city of Montgomery (Montgomery County) apparently is the hub of at least three and possibly four emerging growth corridors. For example, Dale and Pike counties constitute an apparent growth corridor between the cities of Montgomery and Dothan (Houston County). This corridor, as in most cases, seems to follow the major transportation artery linking the two cities. Urban development along the route (US-231) has been heavy. Completion of construction making the route a four-lane divided highway will certainly tend to accelerate the construction of ribbon developments and will probably help to attract light industry to towns with direct access to the highway. In addition, the town of Ozark in Dale County has expanded southward along Alabama highway 85 toward the small town of Pleasant

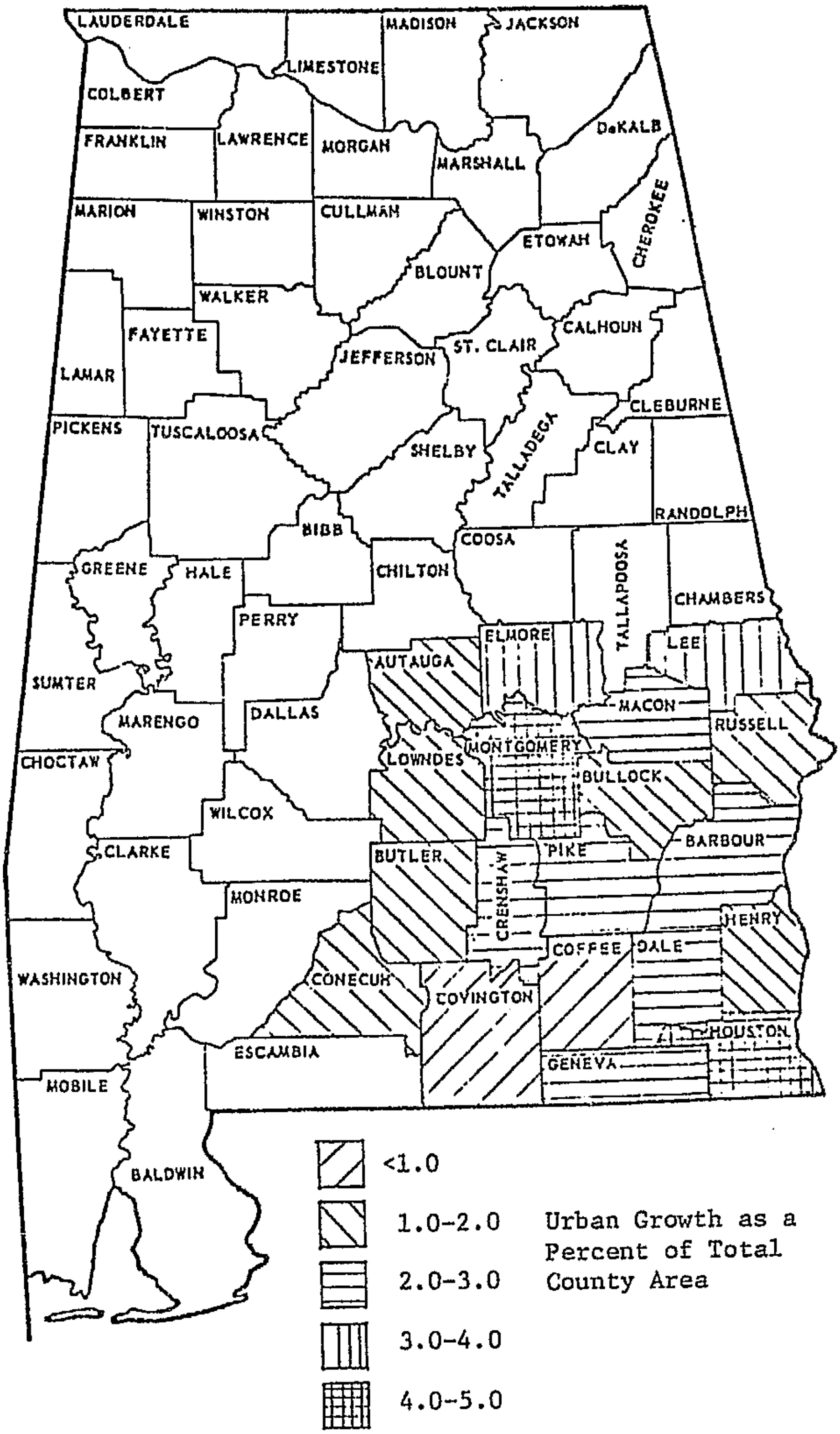

Figure 36. Pattern of Urban Growth in the Target Study Area.

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Hill which in turn is developing toward Fort Rucker. The commercial and industrial market at Fort Rucker as well as the aesthetic appeal of nearby Lake Tholocco no doubt played a major role in this expansion.

Macon County, which increased over two and one-half percent in urban area since 1964, is a definite expansion corridor for the cities of Montgomery and Auburn-Opelika (Lee County). This corridor follows I-85 running eastward from Montgomery County up through the Auburn-Opelika area and further along US-431 toward Phoenix City. Auburn and Opelika have grown together along this route and together are extending along I-85 in the direction of Montgomery. Growth of the city of Tuskegee as well as of other towns in Macon County are also believed to have benefited from this highway. Increased trade and travel between the commercial, industrial, and governmental center of Montgomery, the educational center at Auburn, and the markets of Atlanta, Georgia, should stimulate further growth in the area.

A substantial urban growth in Elmore County may indicate the development of an urban thrust from the city of Montgomery toward the commercial and industrial center in Jefferson County to the north. The development of urban areas along I-65 would seem to reinforce this observation, but further detailed analysis involving more of the northern counties would be required to determine its actual existence.

A fourth growth corridor is indicated by urban development in Lowndes, Butler, and Conecuh counties. Again, a major transportation artery is the center line of this corridor which follows I-65 from Montgomery to Mobile.[36] The establishment of a "superport" off the coast of Alabama should give this corridor one of the highest growth potentials in the State.

A possible expansion corridor seems to be developing between Dothan and the Phoenix City (Russell County) area along the Chattahoochee River as indicated by a substantial urban increase in Barbour County, primarily at Eufaula on the W. F. George Reservoir. Unlike the previously discussed expansion corridors which followed major transportation routes linking population centers, the Dothan-Eufaula-Phoenix City corridor would seem to owe its urban growth more to the multi-use potential of the W. F. George Reservoir and the Chatahoochee River; US-431 would also play a significant role.

Several secondary urban expansion corridors are indicated by Figure 35. For example, US-82 between Montgomery and Midway in Bullock County and Comer, Batesville, and Spring Hill in Barbour County. The growth of these towns may indicate a possible secondary growth corridor. An interesting pattern of urban growth has developed parallel to the corridor just described. It lies for the most part in Macon County along Alabama highway 26 and the Seaboard Air Line Railroad running eastward out of Montgomery. In Russell County, this ribbon of urban developments continues to follow highway 26 which is now paralleled by the Central of Georgia Railroad line heading up to Phoenix City and Columbus, Georgia.

Finally, urban expansion along Alabama highway 52 from Dothan to to Geneva (Geneva County) warrants attention as a possible growth corridor between Dothan and the military and resort center of Pensacola, Florida. All of these primary and secondary corridors as detected from ERTS-I data are represented in Figure 37.

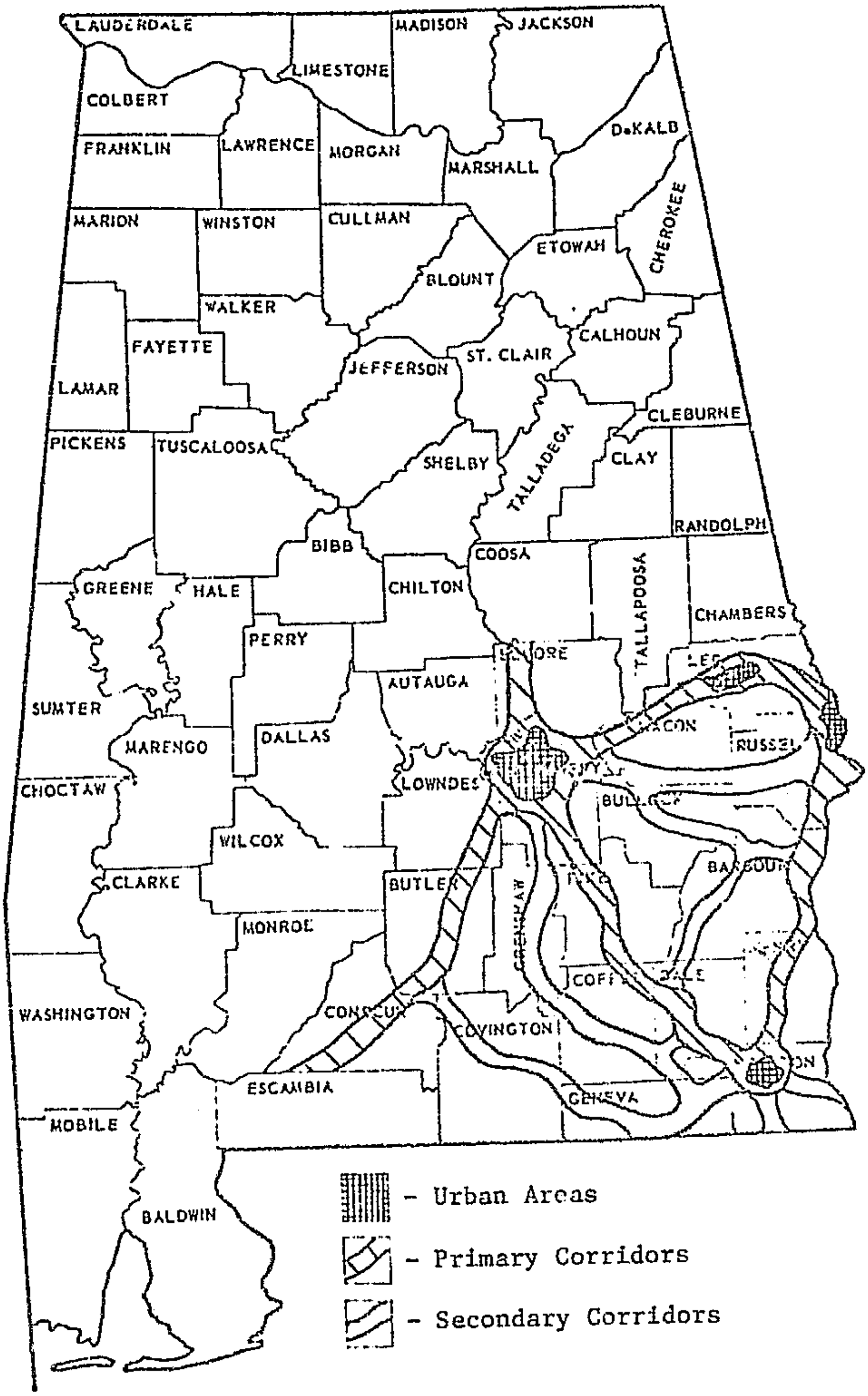

Figure 37. Urban Expansion Corridors Detected from ERTS-I Imagery.

Figure 35 is a graphic demonstration of ERTS-I's ability to monitor and detect land-use change accurately and at a cost much less than by conventional methods. Urban and regional planners, armed with this timely and comprehensive information, will be better able to make vital decisions quickly and efficiently.

THE FEASIBILITY OF OPTIMUM SITE LOCATION
USING LAND-USE DATA FROM ERTS-I

5.1 Background

Confrontations between developers and environmentalists have increased over the past ten years and are sure to continue as the demands of a growing population are satisfied. In the past, these confrontations have resulted in either developing an area beyond its capabilities or prohibiting any development in the area. To resolve this dilemma, regional planners and industrial developers need an analytical technique which will allow them to investigate suitable development alternatives.

This chapter describes such a technique using ERTS-I imagery as the basic data source. It involves a "macro" or regional location search procedure to find the most favorable regional locations for an industrial development. Such an analysis has been performed by the Four Corners Regional Commission over large areas of Arizona, Utah, New Mexico, and Colorado using a computer composite mapping system.[38] No such analysis has as yet been accomplished using satellite imagery as the basic source of information. It was the purpose of this chapter, therefore, to determine the usefulness of ERTS-I imagery by applying it to an optimum site location procedure.

In locating a new plant site, an industry must identify a specific set of requirements which are important to that industry. For example,

industries may require certain raw materials in the near proximity, a specific type of labor market, or accessibility by truck, train or barge. Each industry will have its own set of vital elements and relative costs or weights.

To satisfy these industrial location requirements and to affect sound regional planning, the multiple factor search for optimum location must first be done on a macro scale, a region or even an entire state. All too often, however, an industry simply considers only a few sites within the region and then negotiates with local officials for additional improvements. By using timely land-use information from ERTS-I, however, industries can now systematically scrutinize an entire area easily and efficiently. Once this process has detected apparent suitable sites on the large scale or regional level, the search process can shift to a more detailed "micro" evaluation using socio-economic data and physical parameters not detectable by ERTS-I.

5.2 Choice of Parameters

In demonstrating the usefulness of ERTS-I imagery through an optimum site location program, it was first necessary to define a suitable cell size, the type of "test" industry, and the locational criteria. The procedure was applied to a 20,800 square kilometer area lying entirely within the nineteen county target study area (Figure 38).

A ten by ten kilometer square cell size was selected. On a regional level, a smaller cell size would have been inappropriate, requiring a more exacting local or "micro" analysis of the environment far beyond ERTS-I's capabilities. Conversely, a larger cell size would

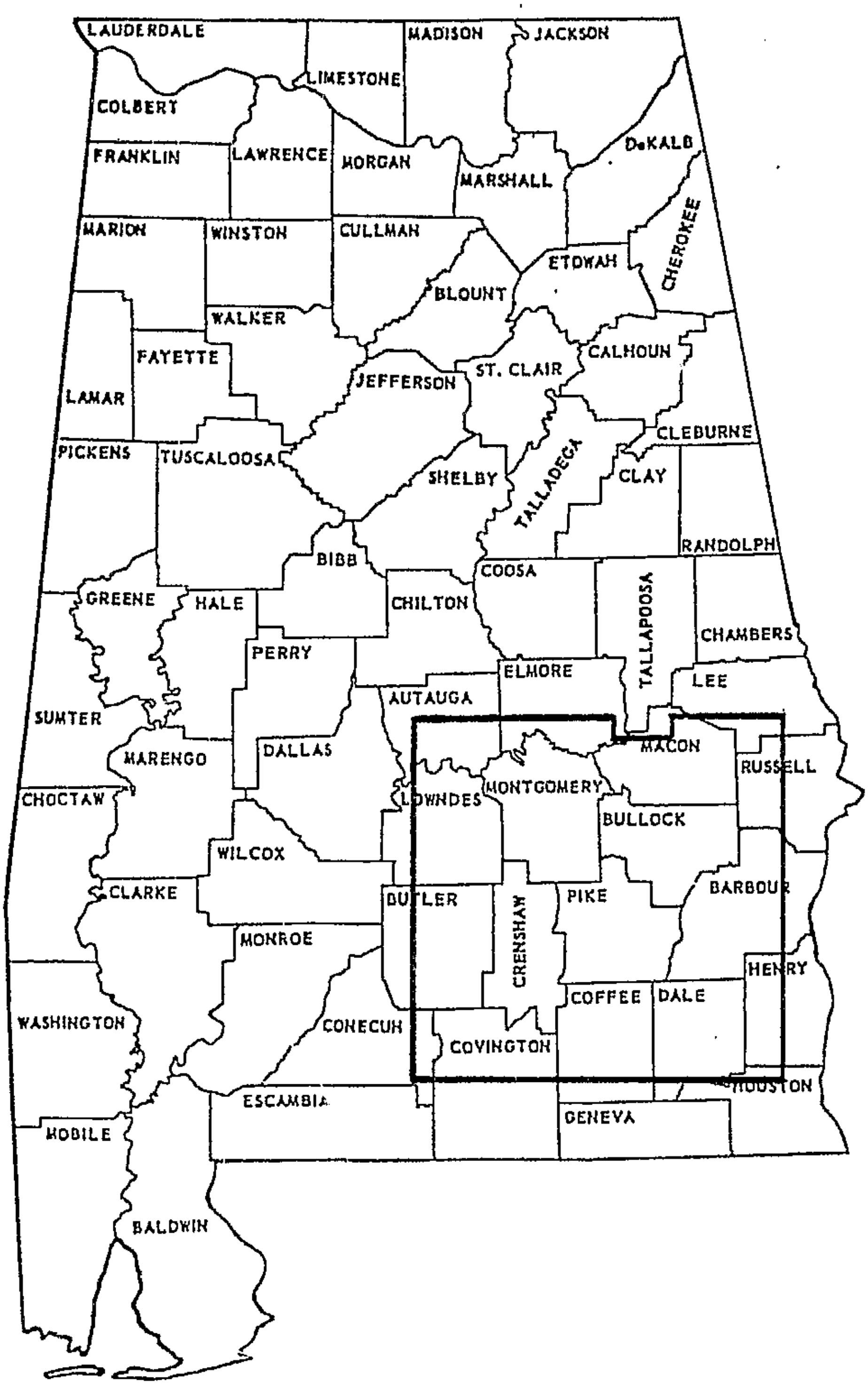

Figure 38. Optimum Site Location Test Area.

have generalized the information to such an extent that it would have been self-defeating.

For demonstration purposes, an industry type was selected which would utilize as many ERTS-I detectable parameters as possible. Since the target study area had primarily an agricultural economy, the obvious choice was that of an "agro-industrial" development which would utilize many types of farm products. This development would be an agglomeration of industries, some of which would use farm produce as their chief raw material while others would produce goods for use on the farm.

The locational criteria were chosen which would best demonstrate ERTS-I's value in this type of procedure. For the most part, these physical parameters are applicable to almost every industrial development, thus suggesting ERTS-I's versatility. The weights given to each of these parameters would change from industry to industry and from region to region.

The following parameters were chosen:

1) Market and Labor Availability
2) Agricultural Rating
3) Plant Site Availability
4) Availability of Surface Water
5) Growth Potential
6) Accessibility by Roads
7) Accessibility by Railroads

Market and labor availability is important to any industry and an agricultural industry is no exception. Urban centers must be of sufficient size to supply the required facilities to the company as well

as a trained labor force. This involves a broad tax base and community acceptance and also well equipped vocational and high schools. These socio-economic factors would, of course, only be applied on the local level. Therefore, the number of urban cells per macro cell (100 square kilometers) was taken to represent an available market and labor potential.

The agricultural rating of each macro cell was important to the agro-industrial development used in this demonstration. It referred to the number of dominant agricultural cells in the macro cell. It was important that this type of development be close to the agricultural activity because of the perishable nature of the raw materials and because services offered by the development would be needed as quickly as possible, especially during critical seasons of the year.

The availability of plant sites is another important consideration. In an agricultural region, farm land is at a premium; therefore, industries using farm products should strive to be close to the farms and yet not displace the agricultural activity. Since urban and agricultural land are already in production and water and wetland are unsuitable for the location of an industry, forest dominated cells in each macro cell were considered to represent suitable construction sites.

Since this region has an abundant water supply underground as well as on the surface, the availability of surface water was not a critical factor. Nevertheless, water is readily detectable on ERTS-I imagery and could be important to an industry requiring supplemental amounts of water for its processes. Aesthetic appeal of a nearby lake or reservoir and the economic benefits of a navigable stream would, in some

cases, be important. Therefore, the number of water dominated cells per macro cell was included.

The growth potential of the area was considered to be one of the most important criteria. Referring back to Figure 36, the primary corridors were given the highest rating, the secondary corridors the next highest, and all other areas were given a value of zero. These growth corridors, detected by an analysis of ERTS-I imagery, were indicative of an expanding urban economy which is a prerequisite to urban development.

Transportation, whether by truck or train, greatly influences the location of an industry by affecting a compromise between locating near the market and near the source of raw materials.[39] In this case, interstate highways were weighted heavier than railroad lines.

Of the seven parameters listed previously, information concerning the first five was extracted directly from ERTS-I images or products thereof. The sixth and seventh parameters were taken from U.S.G.S. 1:250,000 topographic maps, although the routes or several new interstate highways had previously been plotted on the maps using ERTS-I imagery.

5.3 Data Handling

Data for each of the 100-square kilometer macro cells were collected from dominant land-use maps described in chapter four, Section 4.1.2. In gathering the data, a template enclosing one square macro cell was laid over the ERTS-I dominant land-use map of the county corresponding to that part of the region being scrutinized. The number of cells of

each land use was then counted and recorded under the appropriate heading. For instance, a total of three urban cells would give the macro cell containing them a market and labor supply rating of three percent. In such a manner, a map of the first four parameters with each macro cell containing the value of a particular parameter. A map of growth potential for the area was generated by assigning a value of "100" to a macro cell contained in a primary corridor, "50" to a macro cell in a secondary corridor, and "zero" to all other cells. Urban areas in Figure 36 were also given the value of zero since their potential for additional urbanization was zero. Data concerning the last two categories, highways and railroads, were gathered by counting the number of cells per macro cell which contained a primary state or federal highway or railroad line. The value in each cell was then multiplied by a numeric weight corresponding to one of the seven parameters. The resulting weighted values of the same cell in all seven categories were then summed and divided by "20," the sum of the weights, to obtain a numerical value representing that macro cell's suitability for the location of an agro-industrial development. The weights imposed on each of the seven criteria are given below:

1)	Market and Labor Availbility	4
2)	Agricultural Rating	3
3)	Plant Site Availability	4
4)	Availability of Surface Water	1
5)	Growth Potential	4
6)	Accessibility by Roads	3
7)	Accessibility by Railroads	1
		20

Although the procedure outlined above was accomplished manually for this investigation, it was designed specifically for future computer application. The same land-use data used in the change detection analysis of the preceding chapter and already in the computer data file could be utilized in a location search technique based upon weighted computerized map combinations. Information concerning access routes as well as socio-economic factors will also have to be entered into the data file to facilitate subsequent micro cell evaluations. With such data in computer format and with ERTS-I providing synoptic updating of the land-use data file, it will be a simple matter to supply industries, public services, and state planning agencies with optimum location maps based upon their sets of weighted criteria. In addition, elimination of manual compilation and comparison of data will facilitate inspection of regional or state-wide areas using even smaller macro cells than used in this demonstration at less time and cost.

5.4 Results

The results of the procedure discussed in the previous section are contained in Figure 39. Each of the two digit numbers lies at the center of a macro cell and designates that cells "suitability" for the location of an agro-industrial development.

It is evident from Figure 39 that there are two "optimum" macro cells in the test area. The first has a UTM designation of 530520 and contains the city of Greenville, in Butler County. The second has a UTM location of 620470 and contains the small town of Pleasant Hill as

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................0000++++............        ------------........
.18..19..18.0410+37+.18..18..18.        -23--21--20-.19..19.
............0000++++............        ------------........
............0000++++0000000000000000....----...----.........
.17..17..18.0410+30+0430041004100420.19.-22-.18.-20-.18..18.
............0000++++0000000000000000....----....----........ - 580
----........0000----++++++++--------................----++++
-20-.17..19.0410-28-+38++37+-28--28-.19..19..18..19.-20-+30+
----........0000----++++++++--------................----++++
............++++----++++----....--------++++++++++++----....
.19..18..16.+38+-29-+38+-20-.16.-28--29-+31++32++31+-29-.18.
............++++----++++----....--------++++++++++++----....
........++++--------++++--------....++++++++++++............
.18..17.+38+-20--28-+37+-22--20-.19.+30++30++32+.19..19..18.
........++++--------++++--------....++++++++++++............
........++++....--------0000----................++++++++----
.19..19.+39+.19.-20--28-0400-20-.18..18..19..19.+31++31+-22-
........++++....--------0000----................++++++++---- - 540
----00000000....--------++++............----........++++++++
-20-04300440.18.-20--29-+37+.19..18..19.-20-.18..19.+30++32+
----00000000....--------++++............----........++++++++
----⊠⊠⊠⊠----....--------....0000----............----........
-20-⊠48⊠-21-.18.-20--29-.18.0410-20-.19..18..18.-28-.18..19.
----⊠⊠⊠⊠----....--------....0000----............----........
00000000........----........0000....----....----........----
04100420.18..17.-28-.19..19.0430.18.-20-.19.-27-.17..19.-22-
00000000........----........0000....----....----........----
0000--------....++++----....++++++++....++++............----
0440-20--20-.19.+31+-20-.18.+39++37+.19.+30+.19..17..17.-21-
0000--------....++++----....++++++++....++++............---- - 500
0000....----....++++++++........++++0000++++............0000
0410.18.-20-.19.+31++31+.19..18.+38+0420+33+.18..19..18.0430
0000....----....++++++++........++++0000++++............0000
++++............--------........----00000000............0000
+30+.18..19..19.-20--28-.19..19.-21-04100440.19..19..17.0400
++++............--------........----00000000............0000
----++++............----++++++++--------⊠⊠⊠⊠----....++++....
-21-+30+.18..18..18.-20-+31++32+-21--21-⊠45⊠-20-.17.+38+.19.
----++++............----++++++++--------⊠⊠⊠⊠----....++++....
----++++++++++++--------....----++++--------0000----0000....
-20-+31++34++34+-21--20-.18.-28-+31+-22--22-0400-20-0400.19.
----++++++++++++--------....----++++--------0000----0000.... - 460
|         |         |         |
520       560       600       640
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....	----	++++	0000	⊠⊠⊠⊠
. .	- -	+ +	0 0	⊠ ⊠
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< 20	20-29	30-39	40-45	>45

Relative Suitability

Figure 39. Optimum Site Location Map

well as the southern most portion of the city of Ozark. Both macro cells contain major transportation arteries and lie in primary urban growth corridors.

It is obvious that the locating of such optimum areas greatly simplifies the problem of industrial location. With such a tool, industries could immediately identify the areas best suited to their needs and then consider just those areas on a local level. State planning agencies could initiate wise regional planning by restricting the industrial site location process to certain areas or growth corridors thereby promoting, restricting, or prohibiting urban growth according to the region's capabilities.

CONCLUSIONS AND RECOMMENDATIONS

6.1 General

ERTS-I was lauched as an experimental model to test its sensing and telemetry systems and to determine its usefulness as a tool in solving environmental problems. The results of this investigation indicate that using ERTS-I imagery for land-use inventory and planning on the regional level is not only feasible, it is preferable over more conventional sources of information. Detailed local urban planning would, of course, require large scale, low altitude imagery and substantial ground truth. On the other hand, data compilation for an entire state or region using large scale imagery would prove prohibitive in both time and money. For example, land-use information was extracted from ERTS-I imagery for an entire county in about one and one-half hours. This compares to a period of fifteen hours required for the land-use inventory of the same area using air photo mosaics. It is evident, therefore, that a complete and timely land-use inventory could be accomplished for all 67 counties in Alabama after each four day pass of the satellite and before the next sequence of passes eighteen days later. This constitutes a significant achievement over the seven months required using conventional air photo mosaics which were, at best, two years old.

Although the emphasis of this study was on regional land-use inventory and planning, results of other investigations also demonstrate the utility and versatility of ERTS-I data. It is the opinion of the writer, however, that ERTS-I has its greatest potential in the field of regional planning.

6.2 Recommendations for Further Study

Cities and towns can be mapped from ERTS-I imagery and then compared to historic data to detect the amount of areal change that has occurred. A study comparing population growth to this areal growth would benefit city planners in predicting future urban sprawl based on population growth statistics. Conversely, such a study might result in a method of predicting a town's population and population increase by its geographic extent as detected by ERTS-I.

It is important to remember that ERTS-I is not a solution in itself, but only a tool to be used in solving problems of the environment. Therefore, a study should be initiated to investigate the "applied" resolution capabilities of the satellite's sensors; i.e., at what scale and for what purposes are ERTS-I images preferable over other sources of data and when are they not. This study might also reveal the accuracy with which land-use can be extracted from ERTS-I imagery. Although trends in land-use development can be predicted accurately on the regional level from land-use change maps, it is important that the type of change and the accuracy of ERTS-I in detecting it on the local level be known.

The synoptic coverage afforded by ERTS-I should be utilized to investigate local changes in ground cover among the four seasons of the year. It was previously stated that agricultural land was more easily delineated on January imagery when the fields were barren than on September imagery when the fields were still supporting a vegetative cover. This type of study may furnish a procedure whereby certain types of land use are mapped using imagery from the best suited season of the year.

After the land-use inventory using ERTS-I imagery is complete for the entire state, the data file should be expanded to include transportation arteries and selected socio-economic factors. This would enable optimum site location analyses to be run for any region in the state. Likewise, the urban trend analysis described in chapter four should be expanded to the rest of Alabama.

Finally, an industrial air pollution survey should be attempted. This would involve detecting smoke plumes on ERTS-I imagery, pinpointing their sources and mapping their extent, thereby providing a means of determining the areas most affected by air pollution and perhaps modeling the dissemination patterns.

6.3 Conclusions

This investigation has demonstrated the feasibility of efficiently collecting timely land-use data over large regions of the state. Furthermore, it is evident from the preceding chapters that change detection using ERTS-I imagery, at least on the regional level, is possible, and that growth trends based upon these changes will be of significant

benefit to regional planners and policy makers. Finally, it has been shown that industrial developments and/or public facilities can be quickly and efficiently furnished with optimum construction areas using, to some degree, parameters derived from ERTS-I data. Computerization of the technique described in chapter five will greatly enhance this procedure and will allow its expansion to composite maps of many pertinent variables important to a particular development. It is the writer's conclusion, therefore, that not only the feasibility, but also the practicality and preferability of the ERTS-I satellite has been demonstrated but that its full potential will not be realized for many years to come.

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AN INVESTIGATION TO DETERMINE THE OPTIMUM MONITORING SITES FOR PLANNING ERTS DATA COLLECTION PLATFORMS IN A RIVER BASIN

Lamar Larrimore

SECTION SEVEN

of

VOLUME TWO

INVESTIGATIONS USING DATA IN

ALABAMA FROM ERTS-A

The enclosed Masters Thesis was written
in connection with the project:

INVESTIGATIONS USING DATA IN ALABAMA
FROM ERTS-A

Contract NAS5-21876
(Proposal No. 271)

Principal Investigator

Dr. Harold R. Henry (UN604)

Thesis Title

"An Investigation to Determine the Optimum
Monitoring Sites for Planning ERTS Data Collection
Platforms in a River Basin"

by

Charles Lamar Larrimore

Submitted to

Goddard Space Flight Center
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CHAPTER I

INTRODUCTION

1.1 General

A new and comprehensive view of Earth is needed to cope with environmental problems, as well as with difficulties caused by an expanding population and the depletion of natural resources. Earth must be viewed in its entirety as problems with the air-ocean-land system are global in extent. Earth-orbiting satellites, including the Earth Resources Technology Satellite (ERTS), have been developed which are able to remotely sense the Earth's features as well as the data collected by specifically designed data collection platforms (DCP).[1]

1.2 The Alabama ERTS Project

The University of Alabama, with the participation of the Geological Survey of Alabama and the Marshall Space Flight Center, has undertaken a study of the feasibility of applying remotely sensed data to the management of natural resources and to the improvement of environmental quality in Alabama. The accomplishment of this purpose will require the following:

(1) Identification and education of users with regard to the potential benefits to be derived from space-acquired data.

(2) Timely interpretation and dissemination of beneficial information to ultimate users, especially policy makers and regulatory agencies.

(3) Analysis of whether or not information from remotely sensed data results in a significant improvement of the user's decision-making ability and actions related to management of natural resources and environmental quality.[2]

The overall objectives of the Alabama ERTS project are summarized in outline form in Table I. In addition, Tables II and III show, respectively, areas of application of ERTS data and professional people who could derive benefits from ERTS data.

Because water is one of the major natural resources and plays an important role in the development of other resources, particular emphasis is given to water resources both as to quantity and quality in the Alabama ERTS project.[3] Therefore, one of the primary purposes of the environmental phase of this project is to test the feasibility of using remotely sensed data in conjunction with ground truth data to monitor, predict, and manage water quantity and quality in our waterways.

There are several applications for this concept to the monitoring and management of environmental quality. One application is concerned with the fast and accurate acquisition of data necessary to meet the needs of water resource managers, which include both regulatory agencies and private industries.[4] Results from data collection platforms strategically placed in a water basin, together with satellite imagery, may be used to characterize environmental factors and provide means to record changes in environmental quality. In addition, the ERTS data from the DCP may be employed in monitoring environmental changes with regard to enforcing state and federal regulations. The collected data may be stored in an information system which would allow access to specific data according to the needs of the user.[2]

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TABLE I

OBJECTIVES OF ALABAMA ERTS PROJECT[3]

A. TO DETERMINE THE APPLICABILITY OF REMOTELY SENSED DATA FROM ERTS FOR:

(1) LAND USE

(2) INVENTORY AND MANAGEMENT OF NATURAL RESOURCES

(3) IMPROVEMENT OF THE QUALITY OF ENVIRONMENT

B. TO DISSEMINATE INFORMATION IN FORMS MOST SUITABLE FOR ULTIMATE USERS:

(1) PUBLIC POLICY TECHNICIANS

(2) DECISION MAKERS

(3) PRIVATE INDUSTRIES

(4) PRIVATE CITIZENS

TABLE II

USES OF ERTS DATA[3]

FLOOD CONTROL	DISASTER DETECTION
SOIL STUDIES	DAMAGE EVALUATION
RESOURCE INVENTORY	SEDIMENT TRANSPORT
SURFACE WATER STUDIES	TRAFFIC STUDIES
MINERAL EXPLORATION	EROSION CONTROL
GROUND WATER STUDIES	IRRIGATION
ZONING	WATER TEMPERATURE STUDIES
GROWTH TRENDS	CROP CONDITIONS
RECREATION	SURVEYING AND MAPPING
MANAGEMENT	AIR QUALITY MANAGEMENT
PESTICIDE STUDIES	WATER QUALITY MANAGEMENT

URBAN AND REGIONAL PLANNING

TABLE III

POTENTIAL USERS OF ERTS DATA[3]

URBAN PLANNERS	CIVIL ENGINEERS
REGIONAL PLANNERS	CHEMICAL ENGINEERS
FORESTERS	AGRICULTURAL ENGINEERS
GEOLOGISTS	MINING ENGINEERS
ECOLOGISTS	GEOGRAPHERS
HYDROLOGISTS	LIMNOLOGISTS
AGRONOMISTS	ENTOMOLOGISTS
BIOLOGISTS	ARCHITECTS
PHYSICISTS	ARCHAEOLOGISTS
ASTRONOMERS	DEMOGRAPHERS
CHEMISTS	LAWYERS
AGRICULTURISTS	UNIVERSITY FACULTY MEMBERS
⋮	⋮

In order to monitor a water basin in an effective and optimum manner, it is necessary that the locations of the data collection platforms be selected such that measurements of water quality parameters at these locations will be indicative of water quality over the entire basin. This study is concerned with developing methodology for selection of these optimum monitoring sites as specifically noted in the objectives given below.

1.3 Objectives

The objectives of this study were:

(1) to develop the methodology, based upon a systematic investigation, for selection of desirable locations for placing remote sensing devices (data collection platforms) in a waterway such that the data collected will be indicative of the water quality over the entire basin.

(2) to select desirable locations for placing data collection platforms in a portion of the Black Warrior River basin.

(3) to develop a mathematical model which may be employed to predict water quality in the Black Warrior basin.

CHAPTER II

MONITORING SYSTEMS

2.1 Conventional Automated Monitors

Changes in water quality, such as those caused by storms, industrial spills, and flow changes from impoundments, often occur suddenly and affect the concentration of many substances of particular interest. For this reason, continuous monitoring of water quality is advantageous in situations where these abrupt changes are likely to occur. Because of the manpower and time requirement involved in standard manual sampling and analysis, testing in water pollution control work has been moving more toward instrumentation.

A typical installation utilizing a continuous, automated monitor is shown in Figure 1. Most automatic monitors have three basic components—sensor system, analyzer phase, and output phase. The sensing element, which is the part of the system in contact with the sample, may be either immersed in the stream or set in flow cells through which the sample is pumped. Because of advantages in design and maintenance, most systems use the flow cell principle; however, when the sensor is directly in the stream, the sample is not affected by pumping, temperature changes, or time of travel through the instrument.

The types of sensors currently available fall into several categories: (1) electrochemical sensors, (2) sensors based on colorimetric or

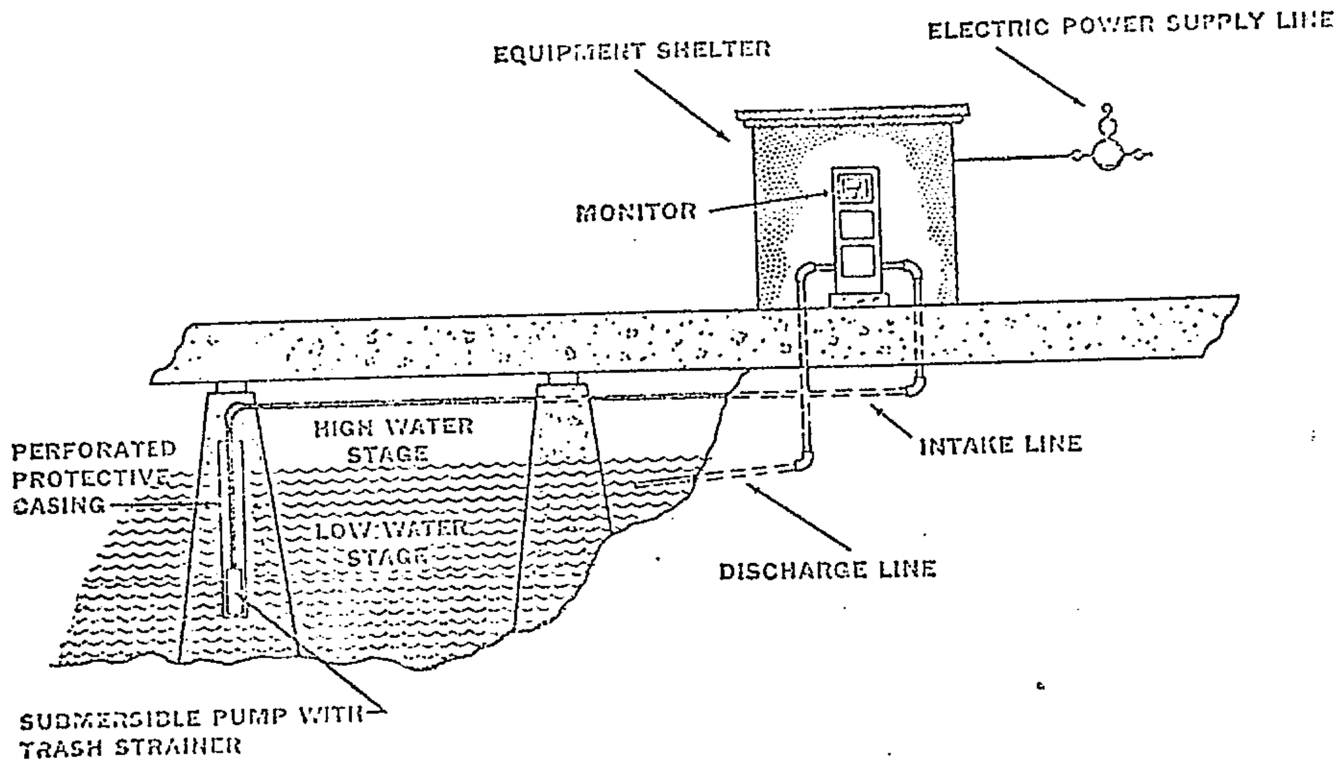

Figure 1. Conventional Monitoring Installation[5]

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light-scattering measurements, (3) sensors measuring temperature through use of a thermocouple, and (4) sensors measuring physical parameters such as velocity.

The analyzer phase of the monitoring instrument converts the signal from the sensor into a voltage to apply to the output phase. The analyzer may be designed to receive signals from one or more than one sensing element.

The output phase of the instrument presents the measured value in the necessary units--pH units, milligrams per liter, micromhos, etc.--and records it permanently. This component normally has a meter panel on the face of the instrument to indicate output to the recording devices.

Where a number of monitoring devices are interconnected to provide a simultaneous evaluation of water quality in a river system, a telemetry system to provide remote handling of the data has almost become a requirement due to the need for speedy collection and analysis of the data.[6]

2.2 Description of ERTS Data Collection Platforms

The instrumentation used in the ERTS program for monitoring water quality, while in some respects similar to conventional instrumentation, embodies some innovative features in its design and construction.

Figure 2 shows a sketch of one of the data collection platforms to be used in the Alabama ERTS project. Its primary components consist of the radio transmitter inside the upper housing, the antenna located on top of the housing, and the sensors, which are included in the lower

PRIMARY COMPONENTS:

1 - Metal Pole (support)

2 - Sliding Fastener

3 - Housing for Analyzer Unit, Battery, and Electronic Unit

4 - Antenna

5 - Connector from Sensor to Analyzer Unit in Housing

6 - Quick Release Pin

7 - Sensor

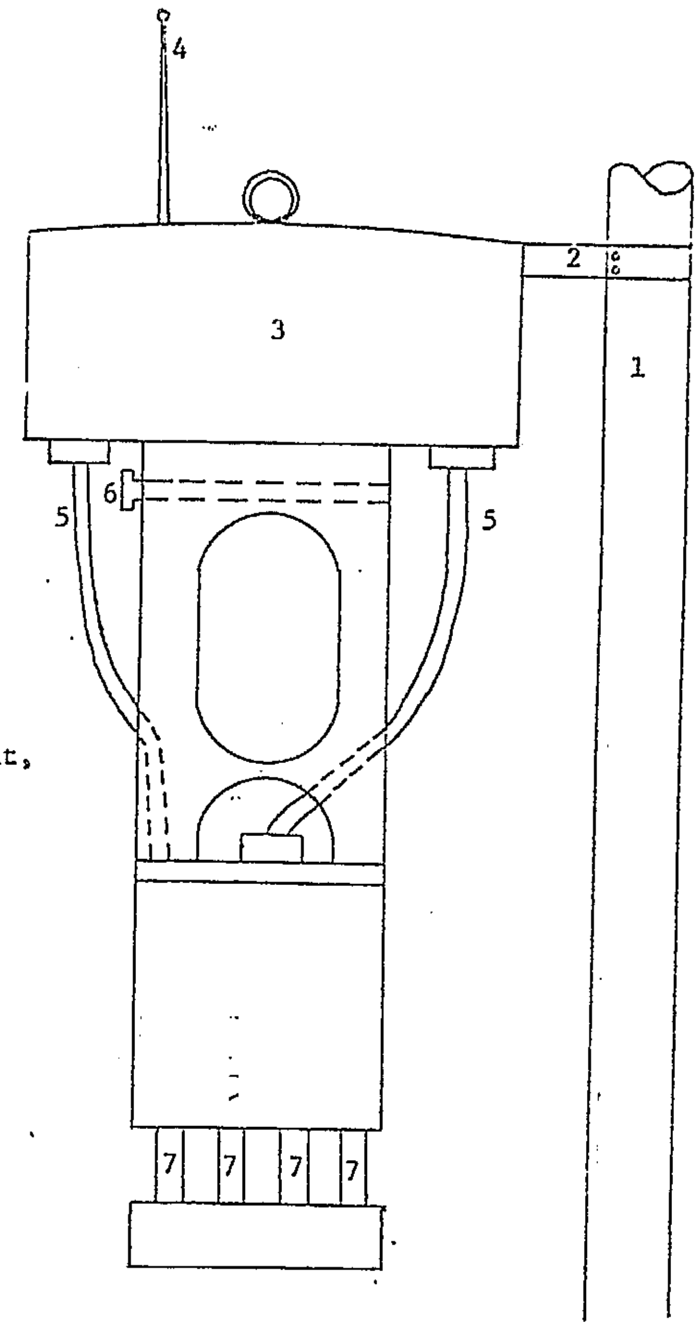

Figure 2. ERTS Data Collection Platform[7]

extremity of the DCP. The instrumentation of the DCP will be fastened to a metal pole which has been driven securely into the river bottom. The fastener will allow vertical movement of the instrument along the pole, facilitating its removal for recalibration and other servicing. The DCP will be submerged except for the antenna and a small portion of the housing, allowing monitoring at a five-foot depth. Another attractive feature of the sliding fastener mentioned above is that it will allow the DCP to float and maintain the five-foot monitoring depth regardless of changes in the water level.

The DCP will be one of three basic units in the overall data collection system, the other two being the ERTS satellite and the ground receiving station. As now planned, the DCP will be activated by a timer shortly before the satellite is due to pass over in any of several adjacent orbits within a line of sight of the DCP. The DCP will remain operational until the satellite has passed overhead, after which the instrument will be deactivated. The water quality measurements taken during this period of operation are immediately beamed to the satellite by means of a radio transmitter and antenna which are part of the DCP itself. Computers on board the satellite will correlate this data received from the DCPs with imagery taken at the same time by sophisticated scanners on board the satellite and transmit the data to the receiving stations on the ground.[7]

Two requirements regarding installation of the DCP are that it be (1) near the shore, where possible damage by contact with river traffic in the main channel will be minimized, and (2) in a position such that the line of sight to the satellite may be maintained. This latter

requirement would exclude areas having high or overhanging cliffs on either bank of the river.

2.3 Comparison of the ERTS Data Collection Platforms with Conventional Automated Monitors

In describing both the conventional automated monitor and the DCP to be used in the ERTS program, several advantages of using the DCP system became apparent. The primary advantage of the DCP is that it allows immediate correlation of water quality data with imagery taken from the ERTS satellite, in order that a methodology might be developed for detecting the occurrence of significant changes in the quality of water. Another advantage is that this DCP data could be used for developing means of detecting changes in basin characteristics and the constituents of runoff from the ERTS imagery.

Another attractive feature of the DCP is that after the satellite comes down there is a possiblity that the DCP could be utilized in the same manner as the conventional automated monitor.

2.4 Parameters Monitored

In the selection of water quality parameters to be monitored, it is important to select those which would be of the most benefit to the ultimate users. It was decided that in the Warrior River basin the parameters dissolved oxygen, temperature, pH, and specific conductance would provide the most beneficial information for the management of basin water quality.[2] Table IV, which lists parameters according to frequency of usage in state water quality standards, indicates that, with the exception of conductance, which is used less than 20 percent of the time, the

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TABLE IV

FREQUENCY OF PARAMETER USAGE IN WATER QUALITY CRITERIA OF STATE STANDARDS[6]

Uniform (100%)	Frequent (99–50%)	Infrequent (49–20%)	Rare (19–0%)
DO	Radioactivity	Arsenic	Bottom Deposits
pH	Public Health Service Drinking Water Stds.	Barium	Chromium (+3)
Coliform		Cadmium	Electrical Conductance
Temperature	Total Dissolved Solids	Chromium (+6)	Ammonia
Floating Solids (Oil-Grease)		Fluoride	Acidity
		Lead	Alkalinity
Settleable Solids		Selenium	CCE
Turbidity and/or Color		Silver	Hydrogen Sulfide
		Suspended Solids	Pesticides
Taste-Odor		Turbidity	Sodium
Toxic Substances		Chloride	Iron
		Copper	Plankton
		Nitrate	Foaming Substances
		Phenols	Boron
		Phosphate	Manganese
		Sulfate	Hardness
		Color	BOD
		Cyanide	MBAS
			Zinc

selected parameters are those uniformly used in formulating state water quality criteria. In view of the fact that state regulatory and planning agencies are anticipated to be one of the principal users of ERTS water quality data, the choice of these four parameters appears to be advantageous.

CHAPTER III

SELECTION OF THE WATER BASIN AREA

3.1 Background

The original plans for this study called for the use of ten DCPs in monitoring the water quality of several river basins on a statewide basis. Later developments indicated that the number of available DCPs would be reduced to the five now allotted to this portion of the Alabama ERTS investigation. Based on this reduction, it was felt that the investigation should be confined to a single river basin to avoid a thin coverage of a multiple basin area, where the data collected would be from relatively isolated and unrelated points. Also, simultaneous evaluation of water quality with ERTS imagery over a large geographical area would be less significant than that produced for a smaller and more extensively monitored area.[8]

3.2 River Basin Selected for Investigation

The sector of the Black Warrior River from river mile 385.0 to river mile 335.0 was chosen for evaluation in testing the utility of the DCP concept for monitoring water quality. Shown in Figure 3, this stretch of the river extends from the confluence of the Locust and Mulberry forks downstream to a point approximately three miles below Oliver Lock and Dam. These limits were selected, in part, because they cover all significant pollutional effluents received by the Black Warrior River from

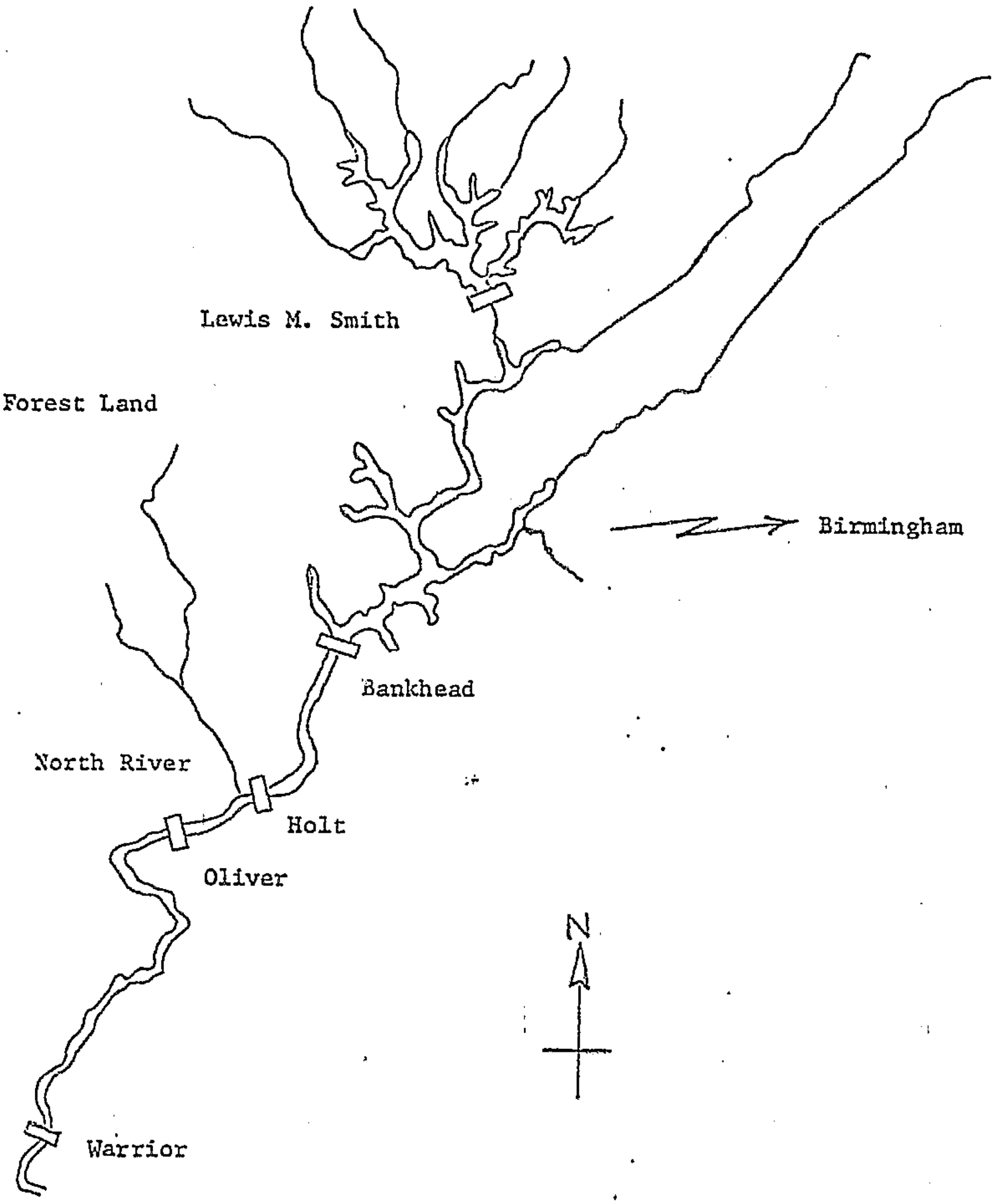

Figure 3. The Black Warrior River Basin

the highly industrialized area in the vicinity of Tuscaloosa. Another unique factor concerning this sector is that the relative quality of the water both upstream and downstream of these limits is good while portions of the area considered are grossly polluted, especially during the low flow periods occurring in the summer months.

The reasons for choosing the Warrior River Basin for the study are summarized as follows:

(1) overall convenience of the basin in regard to data collection and maintenance of DCPs to the primary investigating groups at The University of Alabama, the Geological Survey of Alabama, and Marshall Space Flight Center.

(2) relatively unrestricted use of the river as a receiving body for disposal of sewage and industrial wastes.

(3) location on the river of several major industries, such as chemical, petrochemical, iron products, coking, pulp and paper, and asphalt operations, which discharge wastewaters with varied constitutents.

(4) location of several dams and hydroelectric power generation facilities at Bankhead, Holt, and Oliver, which would allow the investigation of their effects on the quality of water in an impoundment.

(5) presence of both stratified and unstratified conditions in the reservoirs, primarily due to the deep, slow-moving waters in Bankhead and Holt pools and the shallow, swifter waters in Oliver and Warrior pools.

(6) presence of both relatively unpolluted waters, such as Bankhead Pool, and grossly polluted areas, allowing comparative modeling techniques for various degrees of water quality.

(7) potential for additional investigations, such as evaluating the moderating effect of a clean stream (Mulberry Fork) joining a relatively polluted stream (Locust Fork).

The above reasons for selecting the Black Warrior River point out the numerous advantages inherent in selection of this area for investigation during this part of the environmental phase of the Alabama ERTS project.

CHAPTER IV

REVIEW OF LITERATURE

Since the ERTS remote-sensing concept involving correlations of imagery taken from the satellite with water quality data obtained by the DCPs is new and unprecedented, reliance must be placed on previously reported methods for selection of DCP locations and for the development of stream quality models.

4.1 Dissolved Oxygen Models for Flowing Streams and Impoundments

The first dissolved oxygen model for predicting oxygen balance in a flowing stream was developed by Streeter and Phelps[9] in 1925. The formulas, which are based upon two velocity constants, describe the oxygen balance in a stream as a function of distance (or time) from a waste load discharge point. These two parameters are k_1, the deoxygenation velocity constant, and k_2, the reaeration velocity constant. These constants describe the activity in the stream in an all-encompassing fashion, with the effects of several known interacting factors such as photosynthesis and bottom deposits considered as being included in the k_1 and k_2 values.

Other investigators have proposed models which differ somewhat, but all employ the original Streeter-Phelps formulation as the basis of their work. Goodman[10] was one of these subsequent investigators who developed a mathematical model to apply to flowing streams containing no reservoirs and not influenced by estuaries. This particular effort toward water

quality modeling was based on modifications of the original Streeter-Phelps equation and considered dissolved oxygen concentration as the principal criterion of stream quality. These equations determining changes in BOD and DO require input values for deoxygenation and reaeration velocity constants, settling out of BOD to bottom deposits, resuspension of BOD from bottom deposits, and oxygenation by photosynthetic processes.

More recent work involving modeling of flowing streams has been reported by the Texas Water Development Board. The result of this work was the development of a computer program called QUAL-I[11] that is capable of producing a time history and spatial distribution of not only BOD and DO but also temperature and as many as three minerals. This is accomplished within the framework of a completely-mixed, branching stream or canal system with multiple waste inputs and withdrawals. In addition, this agency has developed the DOSAG-I[12] program, which is used to simulate the spatial and temporal variations in BOD and DO under various conditions of temperature and headwater flow.

One of the more useful recent studies done on the subject of modeling dissolved oxygen was conducted by Pyatt,[13] who developed equations for predicting organic matter and DO deficit not only for a free-flowing stream but also for an impounded waterway. These formulations are based on the original Streeter-Phelps equations with added "error" terms to account for the usually omitted factors such as bottom deposits and photosynthesis which affect the deoxygenation and reaeration rates in a stream environment.

The modeling of the reservoir-type situation is particularly noteworthy since relatively few investigators have even attempted such a

study. Due to the lack of previous knowledge in this particular area, complete mixing was assumed for the reservoirs, although this is not actually the case in most impoundments.

Churchill and Nicholas[14] also investigated the changes occurring in the quality of water during its passage through Tennessee River reservoirs and during long storage in impoundments. However, these studies were primarily observations in which no attempt was made toward developing generalized equations for predicting changes in impoundments.

4.2 Water Quality Monitoring Systems

Quite a number of investigating groups have undertaken to set up systems to monitor and control water pollution. Describing all of these in detail would be a formidable task; therefore, only the ones considered applicable to this study are reviewed.

McCormack and Perlis[15] developed a method of optimizing the number and locations of measurement stations needed for a particular monitoring program. In developing this procedure they applied theories of system optimization to a polluted stream model in which the primary dependent variable was dissolved oxygen. The stream models were subject to random variations and environmental changes. Measurement error was a function of the number and position of the measurements, the sample size, and the time between measurements. The developed policy minimized an integral-type function involving mean square error and actual measurement cost.

Other studies, which may not be directly concerned with optimizing locations of monitors, are strongly related to the use of water quality data in water resources management and therefore pertinent to the entire ERTS project. A Harvard research team[16] on the Lehigh River was the

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first group to conduct regional water resource management studies using systems analysis techniques. In recent years, both federal agencies and universities have used systems analysis on river basins, including water quality studies on both the Columbia and the Delaware river systems.

Another group to enter this field of basin management was the Ohio River Valley Water Sanitation Commission (ORSANCO)[17] which in 1960 built an automatic field monitor and a central receiving station to aid in management of water quality in the river basin. Later, more field monitors and data processing facilities were added to make up the integrated system now in operation.

Testerman[18] reported on a system for recording and transmitting digital data at a remote water quality monitoring station that is unattended. Signals from transducers, which measure water quality characteristics, are converted to digital signals and recorded on magnetic tape. This unit can be contacted from a central unit for playback of the day's recording with the transmitted data being recorded by teletype at the central station. The techniques developed in this study hold promise for making water quality measurements in remote areas and at numerous sites and reporting to one central station.

The United States Army Corps of Engineers[6] has also conducted an interesting study involving the control of impoundments to augment flow based on information reported by a monitoring station concerning dilution requirements.

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CHAPTER V

DEVELOPMENT OF THE MODEL

5.1 General

The steps outlined in this chapter were undertaken to develop a technique which would ultimately lead to the selection of the desirable sites for placing the ERTS data collection platforms. It was intended that the methodology developed in this study would find general application for the placement of remotely-sensed monitoring stations.

Since dissolved oxygen is normally considered to be the most important parameter in defining water quality, it was decided that the procedure for selecting DCP monitoring sites would be oriented toward locating the critical dissolved oxygen concentrations in the river basin. For this reason, the modeling technique considered in this study was centered around simulating the dissolved oxygen concentrations normally found in the river.

While dissolved oxygen is considered to be the principal parameter of interest, the additional parameters of pH, temperature, and conductivity are also to be monitored. Factors such as mine drainage and runoff from agricultural lands, which would affect these latter three parameters, were also considered in developing the methodology for selecting the monitoring sites.

In deciding to select locations of monitoring sites based on the most sensitive points for dissolved oxygen, it was felt that the major effects on the other three parameters could also be detected at these same locations. The opposite of this, that is, selecting locations based primarily on monitoring pH, temperature, and conductivity would not necessarily produce locations of meaningful dissolved oxygen concentrations. The reasoning here was that while dissolved oxygen content is very much dependent on time (and therefore distance), factors that would be indicative of changes in pH, temperature, and conductivity, such as dissolved solids content, are largely independent of time of flow, depending instead on the amount of dilution received.

For the reasons discussed above, the technique developed in this study does not simulate pH, temperature, or conductivity, but it does include the capability of receiving inputs for factors affecting these parameters should it become desirable to include these values in modeling studies.

5.2 Factors Affecting Oxygen Balance in Streams

The factors responsible for the occurrence of oxygen variations in streams as well as for the magnitudes of these variations are listed by Goodman[10] as: (1) deoxygenation, (2) reaeration, (3) algal activity, (4) benthal demand, (5) settling and resuspension of BOD, (6) temperature, (7) streamflow, and (8) sunlight. The factors which serve to effect a decrease in dissolved oxygen concentration are deoxygenation due to oxidation of organic matter, benthal demand (bottom deposits), resuspension of organic matter having an oxygen demand, an increase in temperature of the water, and a decrease in streamflow. Conversely, those

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factors which would contribute toward an increase in the dissolved oxygen are reaeration, the photosynthetic activity of algae in combination with sunlight, settling of organic matter having an oxygen demand, a decrease in temperature, and the diluting effect of an increase in streamflow. In Figure 4 a diagram is presented depicting activities which would exert some measure of influence on the BOD and DO systems of the total river environment.

5.3 Streeter-Phelps Equation

The first attempt to mathematically relate the factors affecting the oxygen balance in a natural stream was performed in 1925 by Streeter and Phelps.[9] These investigators combined all the factors adversely affecting dissolved oxygen into a basic deoxygenation equation, while those factors contributing to an increase in dissolved oxygen were combined into a basic reaeration equation. These two equations are shown below in both their differential and their integrated forms.

$$\frac{dL}{dt} = -k_1 L \tag{1}$$

$$L(t) = L_a(e^{-k1t}) \tag{1a}$$

$$\frac{dD}{dt} = -k_2 D \tag{2}$$

$$D(t) = D_a(e^{-k2t}) \tag{2a}$$

In the above equations L(t) and D(t) are, respectively, the concentration of organic matter remaining at time t and the dissolved oxygen deficit at time t. The terms La and Da are, respectively, the concentration of organic matter and the dissolved oxygen deficit at t = 0, while

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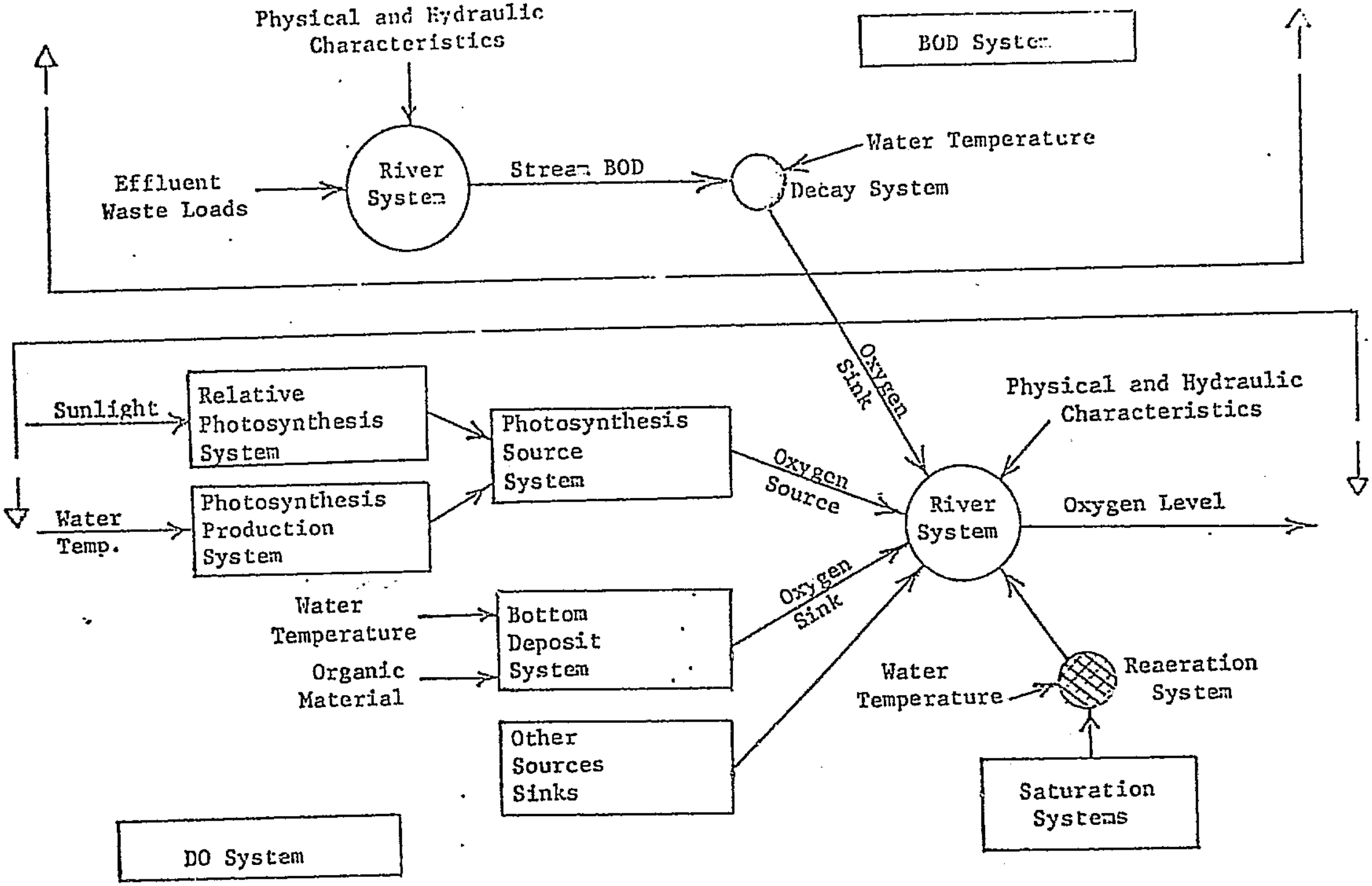

Figure 4. Factors Affecting Dissolved Oxygen

k_1 and k_2 are, respectively, the overall deoxygenation and reaeration rate constants.

Equations (1a) and (2a) were combined to give the well-known dissolved oxygen sag equation shown below in Equation (3).

$$D(t) = \frac{k_1 L_a}{k_2 - k_1}(e^{-k_1 t} - e^{-k_2 t}) + Da(e^{-k_2 t}) \qquad (3)$$

This equation, developed for the case of a free-flowing, non-impounded stream, has remained the basis of nearly all water quality research related to dissolved oxygen.

5.4 Modifications of the Original Streeter-Phelps Equation by Pyatt

While the original dissolved oxygen sag equation developed by Streeter and Phelps has remained largely unchanged, some investigators such as Pyatt[13] have attempted to make refinements, particularly in the area of altering the rate constants to account for factors such as photosynthesis and bottom deposits in some manner other than grossly combining them all together in the k_1 and k_2 rate constants.

Pyatt has proposed accounting for the additional factors in the form of certain "error" terms. He has added a factor r, the deoxygenation error term, to the general deoxygenation equation to obtain:

$$\frac{dL}{dt} = -k_1 L + r \qquad (4)$$

which, when properly integrated, gives:

$$L(t) = (La - \frac{r}{k_1})\, e^{-k_1 t} + \frac{r}{k_1} \qquad (5)$$

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Similarly, Pyatt has added a factor s, called the reoxygenation error term, to the dissolved oxygen sag equation to obtain:

$$\frac{dD}{dt} = k_1L - k_2D + s \qquad (6)$$

which, when integrated gives:

$$D(t) = \left[\frac{k_1L_a}{k_2-k_1} - \frac{r}{k_2-k_1}\right](e^{-k_1t} - e^{-k_2t})$$

$$+ \frac{1}{k_2}(r+s)(1-e^{-k_2t}) + D_a\, e^{-k_2t} \qquad (7)$$

The error terms r and s are usually set equal to 0.005. All other variables in Equations (4) through (7) are as previously defined.

One drawback to the use of Equations (5) and (7) is that they are limited to use with a flowing stream. Recognizing this limitation, as well as the fact that most streams are now regulated to some extent, Pyatt sought to develop equations for the concentration of organic matter and the DO deficit in an impoundment. His efforts resulted in the following equations:

$$L(t) = L_o\, e^{-At} + \frac{ZL_{in}}{A}(1-e^{-At}) \qquad (8)$$

$$D(t) = \left[D_o - \frac{ZD_{in}}{B} + \frac{k_1}{A-B}\left(L_o - \frac{ZL_{in}}{B}\right)\right] e^{-Bt}$$

$$+ \left[\frac{k_1}{B-A}\left(L_o - \frac{ZL_{in}}{A}\right)\right] e^{-At} + \frac{Z}{B}\left(D_{in} + \frac{k_1L_{in}}{A}\right) \qquad (9)$$

where the variables are defined as follows:

L_o = concentration of organic matter in the reservoir before the input of waste flow from upstream

D_o = dissolved oxygen deficit in the reservoir before the input of waste flow from upstream

L_{in} = incoming concentration of organic matter

D_{in} = incoming dissolved oxygen deficit

W = outflow $\div$ volume

Z = inflow $\div$ volume

k_3 = deoxygenation rate constant for sludge deposits on bottom of reservoir

$A = k_1 + k_3 + W$

$B = k_2 + W$

One limitation of Equations (8) and (9) is that complete mixing in the reservoir must be assumed, although this is often not the actual case. Even with this built-in source of error, which would probably cause predicted values of dissolved oxygen concentrations to be slightly lower than those actually found, these equations have been found to be particularly useful in simulating the dissolved oxygen profile of a stream. Pyatt utilized these equations in simulating the DO profile in an actual river basin containing impoundments, showing that the formulae developed in his study do provide accurate results.

5.5 Application of Formulas to Warrior River

When considering the stretch of the Warrior River with which this phase of the Alabama ERTS project is concerned, it became apparent that no single equation can be applied over the entire run of the river from the confluence of the Locust and Mulberry forks to several miles below Oliver Lock and Dam.

This area of the river, which includes all of the Holt and Oliver pools and portions of the Bankhead and Warrior pools, is, in the

strictest sense, impounded over its entire length, suggesting that Equations (8) and (9), developed for use with impoundments, should be used for this entire stretch of the river. This would certainly hold true for the Bankhead and Holt pools, which, in addition to containing the deep, slow-moving waters characteristic of impounded streams, are also regulated entirely by the release of water from Bankhead and Holt dams. However, in the case of Oliver Pool and the portion of the Warrior Pool included in this study, the waters are shallower and faster-moving than in Holt and Bankhead pools upstream. Another factor to be considered is that Oliver Dam is a free-flow dam with the water flowing over the crest. As a result, these waters are subjected to much less regulation than that found at Bankhead and Holt dams, which are not of the free-flow type.

For the reasons enumerated above, it was felt that Bankhead and Holt pools are impoundments requiring the use of Equations (8) and (9) for dissolved oxygen simulation. However, the Oliver and Warrior pools, though technically impoundments, more nearly approach the conditions of a flowing stream, and warrant the use of Equations (5) and (7) which were developed for free-flowing conditions.

It should be emphasized that this step is of paramount importance, requiring careful consideration of the stream under investigation before selecting the appropriate equations for use in simulating the dissolved oxygen profile.

5.6 Reach Concept Applied to the Model

Due to an absence of industries and other such inputs along the impoundments modeled by Pyatt, each of the impounded areas was considered

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as one reach or segment having no subdivisions. This approach lacked sufficient detail to model a complex basin such as the Warrior; however, the modeling equations developed by Pyatt can be applied to the Warrior River by subdividing each impoundment into smaller reaches that are capable of describing additional inputs.

This concept essentially involves separating the entire length of the river under consideration into a number of smaller reaches, such that each reach contains only one input, if any, and also to insure that the physical characteristics of the river remain the same throughout each individual reach.

In order to follow the above guidelines, a new reach is begun whenever one of the following events or structures is encountered:

(1) entrance of a major tributary

(2) the discharge of an industry or a domestic treatment facility

(3) an industrial withdrawal

(4) a dam or other flow-controlling structure.

The first three categories are necessary in order to reflect changes in the quality of water downstream that result from the input of a major tributary or an industrial discharge or withdrawal. The fourth category is necessary due to the nonavailability of a technique for predicting the dissolved oxygen and organic matter below a dam based on the values of these same variables above the dam. A regression method was employed in this study using observed values of organic matter and dissolved oxygen both above and below the dams; however, the correlation coefficient was too small to warrant placing much confidence in the calculated line of best fit through the data. As a result, the alternative is that a new

reach be created at each dam, with observed values of organic matter and dissolved oxygen input into the model below each dam.

This inability to simulate the effect of a dam requires that the model developed herein re-start the simulation process at the upstream end of each impoundment, leaving a gap in the simulated profile at each of the dams along the river.

5.7 Necessary Input for Each Type of Reach

The four criteria outlined in Section 5.6 for designating a new reach result in seven different types of reaches that might be encountered, with the following distinguishing characteristics:

(1) SD--Stream Discharging into the river in a polluted condition

(2) SDH--Stream Discharging into the river and containing High-quality water

(3) R--Restriction to flow, such as a dam or other flow-controlling structure (this reach is normally given a length of 0.6 mile)

(4) N--No input (reach occurs immediately below a dam and is designated as a new reach so that BOD and DO values may be input at downstream end of type R reach)

(5) ID--Industry Discharging into the river (sewage treatment facilities also placed in this category)

(6) IW--Industry Withdrawing water from the river

(7) IWC--Industry Withdrawing water from the river very Close to the discharge point (this reach given a length of zero yet still designated as a new reach in order to remain separated from the discharge)

Due to the differing characteristics of the input to each of the reaches (withdrawal is considered as a negative input), each type of reach will require that different data be input to the model in order that the effect of that input might be properly evaluated. Table V

TABLE V

INPUT DATA REQUIRED FOR EACH TYPE OF REACH

Type of Reach	Reach Number	Month	Upstream R. M.	Downstream R. M.	Input Flow	Intake Flow	Release Flow	River Temperature	Temp. of Input	BOD_5 Input	BOD_5 Downstream End	DO Input	DO Downstream End	$k_1(20)$ Input (Base 10)	$k_1(20)$ River (Base 10)	Average Width	Average Depth
SD	X	X	X	X	X			X	X	X		X		X		X	X
SDH	X	X	X	X	X			X	X			X				X	X
R	X	X	X	X			X	X			X		X		X	X	X
N	X	X	X	X	X			X							X	X	X
ID	X	X	X	X	X			X	X	X		X		X		X	X
IW	X	X	X	X		X	X									X	X
IWC	X	X	X	X		X											

consists of a summary of the data that would be needed to sufficiently characterize the input for each of the seven types of reaches.

5.8 Division of Warrior River into Reaches

Following the outline set forth in the previous sections for the establishment of new reaches, the section of the Warrior River from river mile 385.0 to river mile 335.0 was segmented into 25 different reaches to be considered in simulating the dissolved oxygen profile of the river. Table VI contains a listing of these 25 reaches as well as upstream and downstream boundaries and the major input for each reach.

The actual river mile locations for these reaches were obtained from navigation charts of the Warrior River published by the Corps of Engineers.[20] It should be pointed out that the numbering convention used with the simulation technique employed in this study involves numbering reaches at the upstream end of the stretch under consideration and proceeding downstream.

Another convention adopted in this study is, where possible, to subdivide the river such that the type R reaches begin 0.5 mile above the dam and end 0.1 mile below the dam. The reasoning here is that those conditions which would set apart the waters around a dam from waters in other sections of the river are: (1) large bottom deposits in the forebay, extending perhaps as far as 0.5 mile above the dam, and (2) swift tailrace currents, whose velocities might be maintained for a distance of 0.1 mile below the dam.

In some instances, however, the above policy cannot be kept. Such is the case around Oliver Lock and Dam, where to extend the reach 0.5 mile above the dam would include the discharge from the Northport sewage

TABLE VI

REACHES OF THE WARRIOR RIVER USED IN SIMULATION OF DISSOLVED OXYGEN

Reach	Upstream R. M.	Downstream R. M.	Input
1A	385.00	382.00	Locust & Mulberry Forks
2A	382.00	367.50	Valley Creek
3A	367.50	366.00	Yellow Creek
4A	366.00	365.40	Bankhead Lock & Dam
5A	365.40	361.50	None
6A	361.50	347.50	Davis Creek
7A	347.50	346.90	Holt Lock & Dam
8A	346.90	346.30	None
9A	346.30	345.70	Hurricane Creek
10A	345.70	345.70	Reichhold Chemical Co. Intake
10B	345.70	345.20	Reichhold Discharge
10C	345.20	344.40	A. B. C. Discharge
11A	344.40	344.40	Intake for Warrior Asphalt Co. & Empire Coke Co.
11B	344.40	344.39	Warrior Asphalt Discharge
11C	344.39	343.70	Empire Coke Co. Discharge
12A	343.70	343.50	North River
13A	343.50	343.00	Central Foundry Discharge
14A	343.00	342.50	Gulf States Intake
15A	342.50	341.60	Gulf States Discharge
16A	341.60	338.41	Tuscaloosa WTP Discharge
17A	338.41	338.39	Northport STP Discharge
18A	338.39	338.10	Oliver Lock and Dam
19A	338.10	337.00	None
20A	337.00	336.70	Hunt Oil Co. Intake
21A	336.70	335.00	Hunt Oil Discharge

treatment plant, in which case the requirement specifying only one input for each reach could not be met. To circumvent this problem, the treatment plant effluent was included in a reach of length 0.02 mile and the reach containing the dam was restructured so as to extend 0.3 mile above the dam and 0.1 mile below the dam. This solution provided that each of the two reaches would contain only one input.

5.9 Additional Equations Used

In developing a method for simulating the dissolved oxygen profile of a stream, the most important equations are those which actually predict the concentration of organic matter and the dissolved oxygen deficit. However, there are quite a number of other formulae utilized in providing input values to the final equations. These supporting equations are briefly described in the following sections.

5.9.1 Velocity Rate Constants

The three rate constants are comprised of the biodegradation coefficients k_1 and k_3 and the reaeration coefficient k_2. Commonly, the value of k_1, the constant pertaining to deoxygenation of suspended organic matter, is obtained as the slope of a semilog plot of organic matter remaining versus time. However, in quite a few instances during this study, when any BOD measurements at all had been taken, they usually consisted only of BOD_5 and BOD_{20} (L_a). In such cases the value of k_1 (base 10) was found by utilizing Equation (10):

$$BOD(t) = L_a\ (1-10^{-k_1 t}) \qquad (10)$$

which could be modified to the form of Equation (11).

$$k_1 = -\frac{1}{t} \log \left(1 - \frac{BOD(t)}{L_a}\right) \tag{11}$$

In those cases where no BOD measurements had been taken by some of the industries, the author was forced to rely on some typical k_1 values given by Eckenfelder[21] for certain types of industrial wastes.

According to Pyatt[13] the value of k_3, the deoxygenation rate constant for bottom deposits in reservoirs, can be safely assumed to equal 0.005.

Quite a few empirical formulas have been developed for calculating k_2, the reaeration coefficient. Most are of the general form:

$$k_2 = \frac{CV^m}{d^n} \tag{12}$$

Where V is the mean velocity, d is the mean depth, and C, m, and n are coefficients varying according to the use of each investigator.

The particular formula providing best results with a certain stream varies according to the characteristics peculiar to that stream. Results obtained in this study indicated that the equation developed by O'Connor and Dobbins[22]:

$$k_2 = \frac{12.90 v^{0.5}}{d^{1.5}} \tag{13}$$

provided the most accurate values for k_2 in the Warrior River.

5.9.2 Corrections for Temperature

All of the above methods for calculating the velocity rate constants result in values accurate only at a temperature of 20 °C and,

consequently, these values must be adjusted to the temperature of the water:

$$k_1(T) = k_1(20) \left[1.047\right]^{T-20} \qquad (14)$$

$$k_2(T) = k_2(20) \left[1.0159\right]^{T-20} \qquad (15)$$

$$k_3(T) = k_3(20) \left[1.047\right]^{T-20} \qquad (16)$$

In addition, the value of the ultimate BOD (L_a) must be corrected to the proper temperature:

$$L_a(T) = L_a(20) \left[0.02T + 0.6\right] \qquad (17)$$

In each case, Equations (14) through (17) represent the commonly used methods of correcting that particular parameter for temperature.[12]

5.9.3 Dissolved Oxygen Saturation

In order to determine the dissolved oxygen deficit in each reach of the river, it was necessary to know the saturation concentration of dissolved oxygen for the water in the main stream of the river as well as in the inputs of various tributaries and industrial wastes.

Quite a few references contain tables showing the saturation values of DO at various temperatures; however, in a simulation technique, the saturation values are needed in an equation form which is more easily adaptable to computer programming. The particular empirical formula employed in this investigation for calculating the saturation concentration of dissolved oxygen in water at a certain temperature was

developed by TVA[23] and is shown below:

$$DO_{sat} = 14.65 - 0.41\ T + 0.008\ T^2 - 0.00008\ T^3. \quad (18)$$

5.9.4 Corrections for Changes in Flow

As each new reach is encountered and the particular input for that reach is added to the flow from the reach immediately upstream, it was necessary to correct values of k_1, dissolved oxygen deficit, and concentration of organic matter for the mixed flow. The dilution method is employed in each case:

$$k_1 = \frac{k_1\ Q_{up} + k_1\ Q_{in}}{Q_{up} + Q_{in}} \quad (19)$$

$$D = \frac{D\ Q_{up} + D\ Q_{in}}{Q_{up} + Q_{in}} \quad (20)$$

$$L_a = \frac{L_a\ Q_{up} + L_a\ Q_{in}}{Q_{up} + Q_{in}} \quad (21)$$

where Q_{up} is the flow leaving the reach immediately upstream and Q_{in} is the additional flow entering at the head of the particular reach under consideration.

CHAPTER VI

COLLECTION OF DATA

6.1 General

As previously stated, the primary purpose of this investigation was to locate the optimum monitoring sites for DCPs based upon critical dissolved oxygen concentration levels. The most promising technique to be employed for meeting this objective appeared to be a simulation of the dissolved oxygen profile of the river. It became evident that the period of the year which would present the lowest, and therefore most critical, values for dissolved oxygen would be the summer months of June through September, when the volume of flow is lowest and the temperature of the water is highest. It also appeared logical that the simulation technique and subsequent selection of DCP sites should be based upon the critical monthly average values for dissolved oxygen rather than upon critical daily values, since the monthly values are less subject to variations with respect to location that would normally be encountered with daily values. In addition, the data collected was obtained during the months of the previous summer, in order to assure that the data reflected any recent developments which might cause changes in the water quality of the river.

The nature of a study of this type requires the acquisition of large amounts of data for many parameters in order to characterize adequately

the quality of the water in a river and in the major inputs. Many sources of information were investigated in searching for the data needed to develop the model. Information was obtained from interviews with representatives of the various industries, STORET, the Environmental Protection Agency's data acquisition system, and river surveys conducted by Alabama Power Company[24] and Gulf States Paper Corporation.[25]

It was hoped that STORET, a computer-oriented system devised by EPA for storage and retrieval of water quality data,[26] would be one of the principal sources of information. However, as a result of studying a report by Miller and Walters[27] on the use of STORET in water quality management and gaining some experience with the mechanics of using the system, it was concluded that the data available for the Warrior River was not recent, and therefore of little value in providing input to the model.

The remaining sections of this chapter are devoted to a general discussion of the sources of information resorted to in the search for each type of input data. A detailed listing of the data sources and all data gathered for each reach of the river is presented in Appendix II.

6.2 Velocity Rate Constants

Values of k_1, the overall deoxygenation constant, are necessary for each input of industrial waste or discharge from a polluted stream, as well as k_1 values for the stream flow below each of the dams on the river. The k_1 values immediately below the dams were obtained from BOD_5 and BOD_{20} values measured at these locations by Gulf States Paper Corporation during their summer river surveys.[25] In those cases where BOD_5 and BOD_{20} values were obtained by some of the industries on the river, such

as at Empire Coke Company,[28] k_1 values were obtained through interviews with representatives of the particular industry. When such values were not known, typical k_1 values given by Allen and Bodenheimer[29] for paper mill waste and by Eckenfelder[21] for other types of waste were assumed to apply for the industries in question.

The reaeration rate constant for each reach was computed by the O'Connor-Dobbins formula given in Section 5.9.1, while values for the other constants--k_3, r, and s--were all assumed to be 0.005.[13]

6.3 Dissolved Oxygen and BOD in the River and its Tributaries

The major portion of the data for the parameters was obtained from the previously mentioned river quality surveys conducted during the summer of 1972 by Gulf States Paper Corporation[25] and Alabama Power Company.[24] Additional information was obtained from two publications by the Geological Survey of Alabama pertaining to stream quality.[30,31]

6.4 Industrial Withdrawals and Discharges

The primary source of data on withdrawals from the river for use by industries was an interview with Horn[32] followed by a perusal of the discharge permits on file with the Alabama Water Improvement Commission.

Data concerning the quantities and characteristics of the wastes discharged by the various industries were largely gathered from personal contacts with representatives of the industries--Fuller,[25] Davis,[28] Woods,[33] Witherspoon[34] and Sandifer[35]--while some additional data was obtained from the AWIC files and from historical data tabulated by McClure.[36]

6.5 Flow Rates

Principal sources of data regarding average rates of flow in the Warrior River were provided by Bowers[37] and by an impact study covering the effect of the Holt Dam on the water quality of the river.[24]

Information concerning rates of flow in the tributaries to the Warrior River was found in the USGS publication of flow data in Alabama for 1971[38] and in two publications of a similar nature which were released by the Geological Survey of Alabama.[31, 39] Information on discharge rates from the Tuscaloosa Water Treatment Plant were obtained from records kept at the plant.[40]

6.6 Water Temperatures in the River and its Tributaries

Data regarding temperatures of the water in the river were found to be plentiful in the previously noted river quality surveys conducted by Alabama Power Company[24] and Gulf States Paper Corporation[25] during the summer of 1972. Similar data for the tributaries were found in Circular 36,[30] a publication by the Geological Survey of Alabama regarding surface water quality in Alabama.

6.7 Cross-Sectional Areas

The only recorded measurement of cross-sectional area of the Warrior River was taken above Oliver Lock and Dam by the USGS.[38] Judging from values of width and depth given at this section, it appeared that a trapezoidal cross-section could be assumed for the river with the top width approximately twice the bottom width at that particular section.

Since no measurements of cross-sectional area were taken at other locations and also as there was a lack of information indicating the

general shape of cross-sectional areas, the trapezoidal shape was assumed to apply over the entire stretch of the river considered in the study. Based on this assumption, the area of each reach was calculated by the following equations:

$$A = d/2(W_T + 1/2\ W_T) \tag{22}$$

which simplifies to:

$$A = 3/4 \times d \times W_T \tag{22a}$$

where A is the cross-sectional area, d is the mean depth, and W_T is the width of the water surface.

Values of the width at the water surface at normal pool elevation were scaled off navigation charts of the river published by the Corps of Engineers.[20]

Mean depth for each reach was taken as the difference between normal pool elevation in the particular reservoir containing that reach and the elevation of the river bottom in the reach. Normal pool elevations were taken from a pamphlet published by the Corps of Engineers[41] on the Black Warrior and Tombigbee rivers. Elevations of the river bottom for each reach were taken from information provided by Bowers.[37]

CHAPTER VII

DISCUSSION OF RESULTS

7.1 Comparison of Simulated and Observed DO Profiles

The results of applying the developed simulation technique to the Warrior River are shown in Appendix I in a tabular form printed by the computer program developed by the author for this model. In order to facilitate evaluation of these results, the simulated dissolved oxygen values in Tables VII through X of Appendix I were plotted in Figures 5 through 8 and compared with the profiles based on observed conditions in the same stretch of the river. These measured values of dissolved oxygen were taken from the river surveys conducted by Alabama Power Company[24] and Gulf States Paper Corporation.[25]

Based upon a visual comparison of the simulated and observed profiles, the results, which showed an error of less than 10 percent in most places, indicated that the developed model does provide acceptable accuracy in the prediction of dissolved oxygen content of the river. Some factors contributing to the differences between observed and simulated profiles were: (1) the highly variable nature of dissolved oxygen content in a stream, (2) the assumption of complete mixing used by Pyatt in developing his dissolved oxygen prediction equations for impoundments, and (3) the errors inherent in the measured values, which are monthly averages of observed values at one point in the cross-section

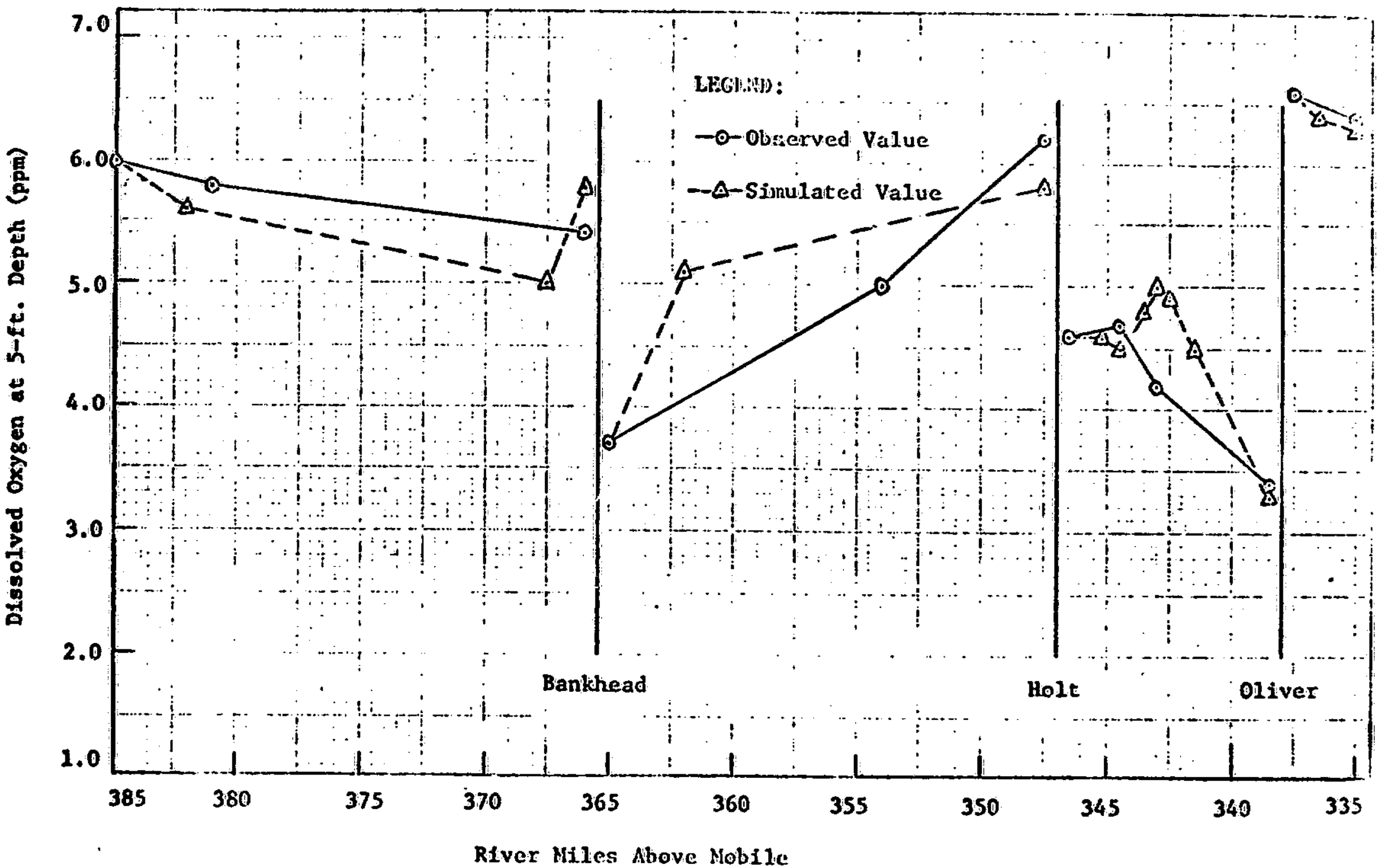

Figure 5. Dissolved Oxygen Profiles of Warrior River (June, 1972)

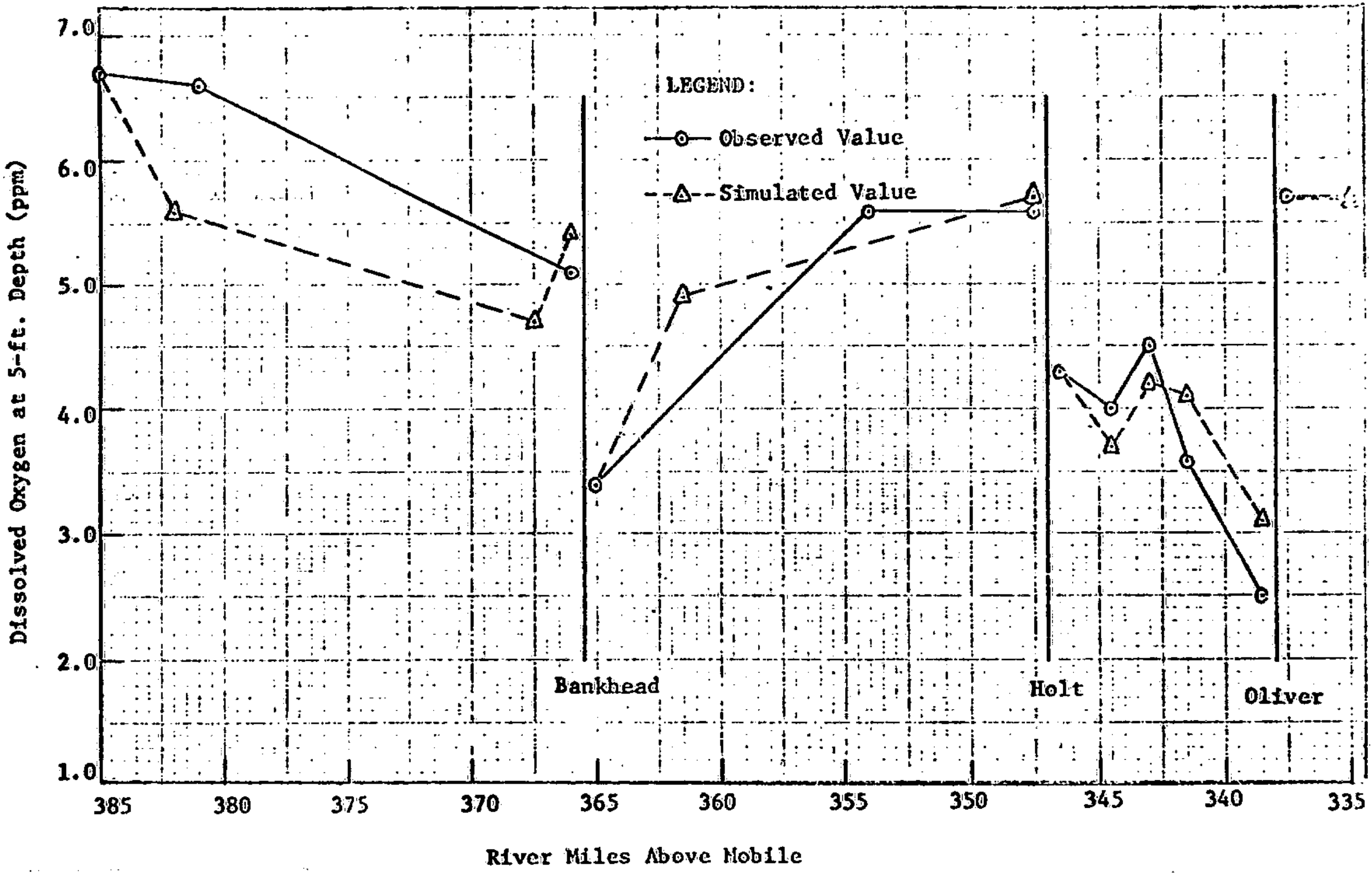

Figure 6. Dissolved Oxygen Profiles of Warrior River (July, 1972)

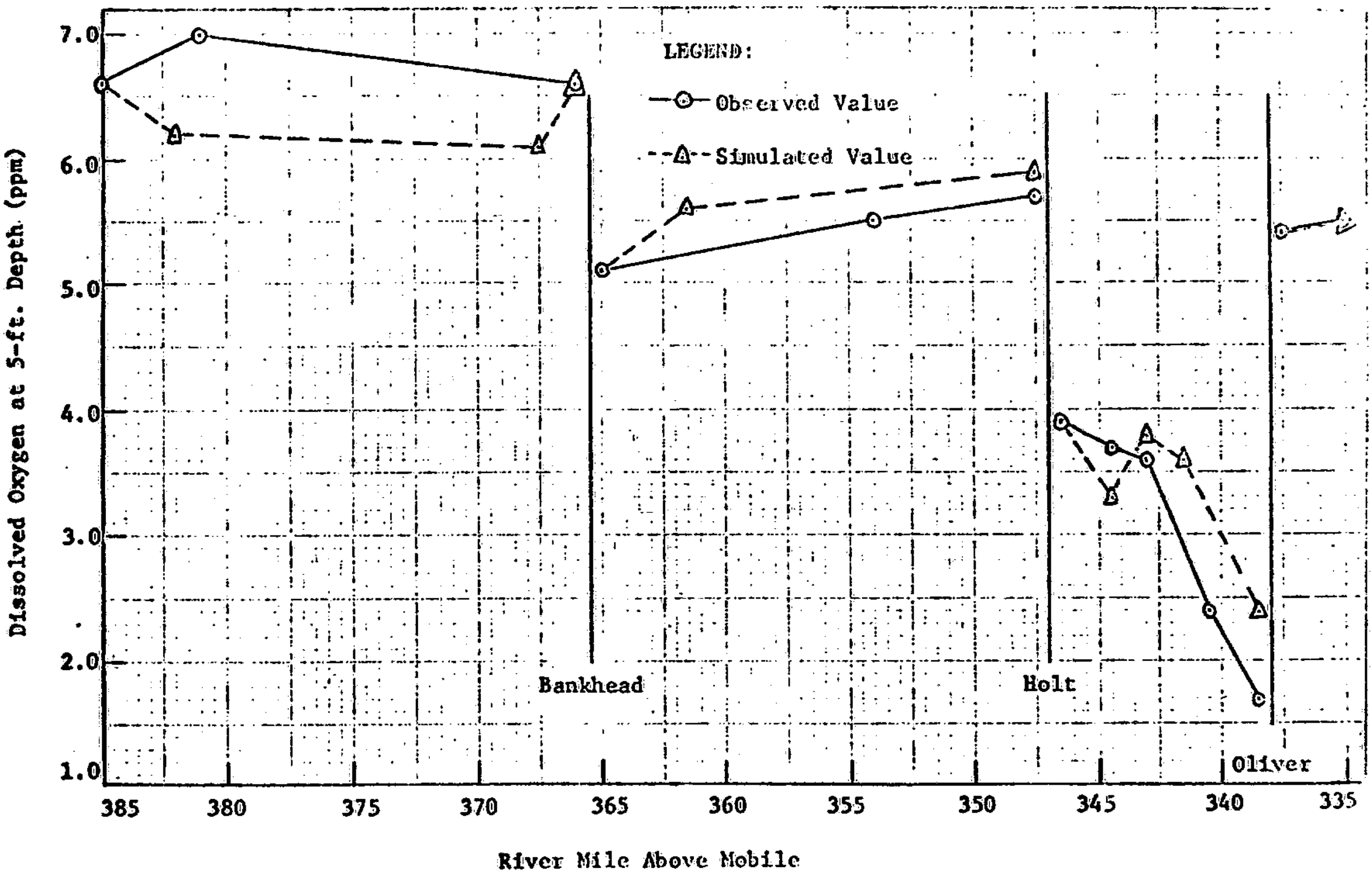

Figure 7. Dissolved Oxygen Profiles of Warrior River (August, 1972)

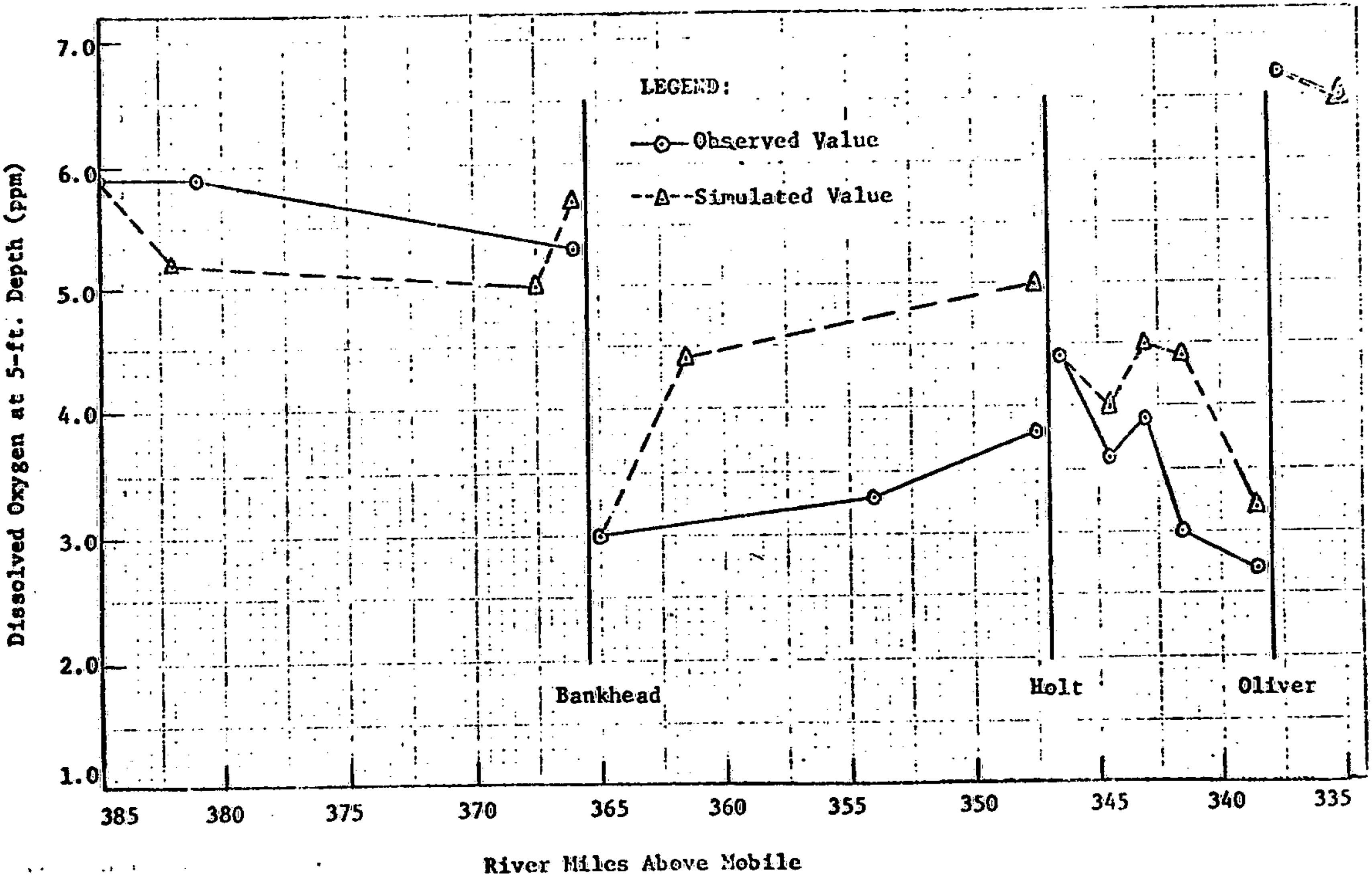

Figure 8. Dissolved Oxygen Profiles of Warrior River (September, 1972)

rather than representations of lateral or vertical profiles within the cross-section.

The lack of observed data at each point was such that the results of a rigorous statistical analysis would have been inconclusive. However, in view of the fact that observed values varied from the means at each point by as much as 10 percent and considering that in most cases the simulated values fall within plus or minus 10 percent of the observed values, the results of the simulation certainly seem to be adequate.

In those cases where the profiles differed by more than 10 percent, the discrepancy can be explained from a physical standpoint. In the Bankhead Pool the simulated profiles for each month exhibited the same general downward trend (proceeding downstream) shown by the observed profiles; however, the simulated values were somewhat lower than the corresponding observed values. This slight discrepancy is considered to be due to the complete mixing assumption employed in the DO prediction equation by Pyatt, Equation (9), which was applied in the highly-stratified Bankhead Pool. As a result, the simulated values represent more of an average of the higher observed values near the surface and the lower observed values at greater depths.

A sharp difference between simulated and observed profiles is noted in the Holt Pool near river mile 362. The observed profiles show an almost linear increase in DO between Bankhead Lock and Dam and Holt Lock and Dam, while the simulated profiles exhibit a much sharper increase in DO immediately below the Bankhead Lock and Dam. This is followed by a more moderate increase in DO from river mile 362 to the Holt Lock and Dam. The difference between the two profiles is probably due to the manner in which the profiles were drawn, that is, by

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connecting both the measured and calculated DO values on these profiles by straight line segments in which the dissolved oxygen values between separated points is not elucidated. The higher simulated dissolved oxygen value near river mile 362 is what one would intuitively expect as a result of the oxygen-depleted waters released from Bankhead Dam undergoing a much more rapid dissolved oxygen recovery than that shown in the observed profile due to the large oxygen deficit at this point and the corresponding high rate of reaeration.

In Oliver Pool the two profiles match quite well, with the simulated values slightly higher in most places. The above situation may be attributed to the use of the Streeter-Phelps equation for free-flowing conditions, Equation (7), which would be expected to yield moderately higher values of DO in a semi-impounded reservoir such as Oliver Pool.

Excellent results were obtained in that portion of the Warrior Pool studied, where the simulated and observed values agreed quite well.

In general, the model seems to work quite satisfactorily in predicting the dissolved oxygen profile of the Warrior River and it is anticipated that both this modeling technique and the supplementary computer program also developed in this study could be successfully applied to any river basin.

7.2 Selection of Locations Providing Optimum Water Quality Data

Since the primary purpose of the analysis performed in this study was to select those points which would provide the optimum water quality data with particular regard to the dissolved oxygen content, the simulated

and observed DO profiles were utilized in accomplishing this objective. The selection of the following points for placement of the anticipated five DCPs was considered most advantageous from the standpoint of providing useful information:

(1) R. M. 385.0 (below the confluence of Locust and Mulberry Forks)--this point would provide data that could be used to evaluate the quality of water entering the section of the Warrior River considered in this investigation. Placement of a DCP here would provide for collection of data that is necessary as the initial input for the system into the developed model.

(2) R. M. 365.0 (one-half mile below Bankhead Dam)--monitoring at this location would give an indication of the quality of water entering the Holt Pool as well as monitoring the point of lowest dissolved oxygen content in that reservoir.

(3) R. M. 346.5 (one-half mile below Holt Dam)--Since Oliver Pool contains almost all the inputs from industries in the stretch of the river studied, a knowledge of the quality of the water entering this area would be of vital importance to effective management and control of this highly used water resource. Based on this reasoning, the placement of a DCP at this particular location would permit evaluation of the water quality before reaching the highly industrialized sector of the river further downstream in the Oliver Pool.

(4) R. M. 338.2 (forebay of Oliver Dam)--A DCP placed at this location would serve a two-fold purpose. First, it would

provide for monitoring of the point of lowest DO concentration in the Oliver Pool. Second, due to the general downward trend of the DO profile from Holt Dam to Oliver Dam, it would provide assurance that an improvement in water quality at this point would be indicative of improved quality in the entire reservoir.

(5) R. M. 335.0 (approximately three miles below Oliver Dam)-- Monitoring performed at this location would provide data to be used for evaluation of the quality of water leaving the investigated area as well as for comparison with data collected at the entry point to the system for which the model was developed.

A map of the entire length of the river studied showing the selected DCP location sites is shown in Figure 9. Detailed maps of the river showing the segments used in modeling, the tributaries to the river, the locations of all significant waste discharges and the DCP locations are presented in Appendix III.

In addition to the reasons discussed above, these particular locations were selected to provide the initial input values of dissolved oxygen for each reservoir required in the developed mathematical model. Thus, values of dissolved oxygen (and other parameters) obtained from a relatively few critical locations may be utilized in the developed model to simulate and predict water quality over the entire reach of the river selected. As an example, values of dissolved oxygen measured by the DCP located just below Holt Lock and Dam (R. M. 346.5) may be used to predict DO values in the Oliver Pool as a function of the quantities and characteristics of the wastes discharged into this segment of the

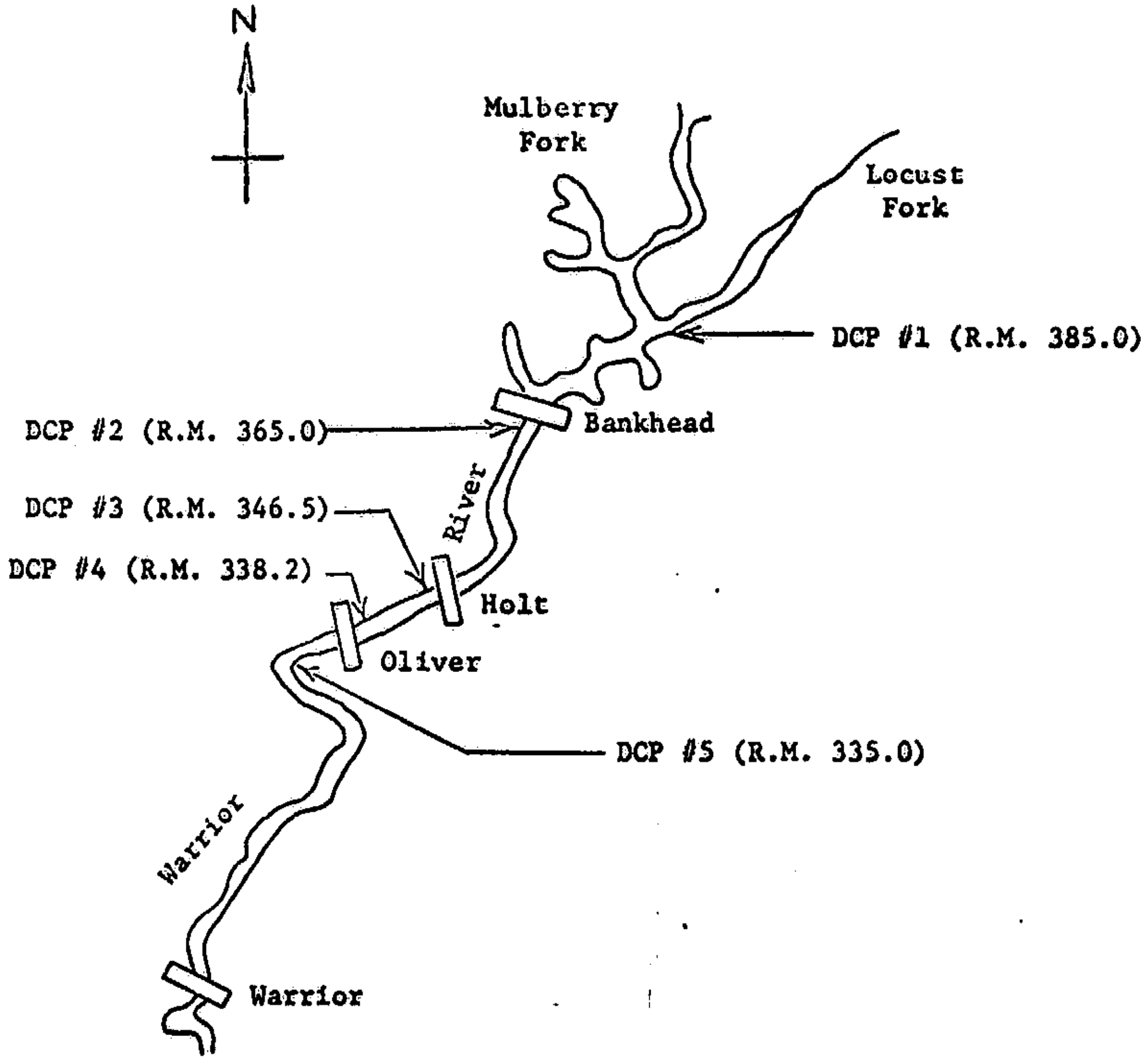

Figure 9. Locations of DCP Monitoring Sites

river. Alternately, the required DO level at this location may be obtained which will produce a desired water quality in the pool under varying loading conditions of discharged wastes. In this latter case, the information provided would assist in determining the amounts and characteristics of water to be released through the dam for a given set of waste inputs such that the desired water quality will be maintained. Additionally, the measured DO value and the resulting simulation model may be employed to predict the optimum point in time for discharge of impounded wastes by the industries in order that the water in the pool will not be degraded below the desired levels. Similar examples may be given for the simulation and management of water conditions in the Holt and Bankhead pools based upon the DO measurements at the DCP locations. Extension of the modeling technique over the entire reach of the river may be performed since water quality data in an upstream segment serves as input conditions to the successive downstream segments.

Although the model developed in this study was based primarily on dissolved oxygen, for the reasons previously given, it is in a form easily adaptable to simulating concentrations of dissolved constituents such as chlorides, sulfates, phosphates, and metals which might be present as a result of drainage from mining operations and runoff from agricultural activities. The net effect of many of these materials on the pH, conductivity, and temperature of the receiving water will be monitored by the DCPs and simulation of these effects may be obtained by use of portions of the developed model other than those applying to the DO prediction equations. For a detailed study of these types of constituents, the DCPs may be moved to appropriate monitoring locations.

Although not investigated in this study, the use of DCP data in conjunction with ERTS imagery may be employed in a basin-wide study of the land use-water quality interaction. As indicated previously, the DCP will detect at its location the residual effect of upstream surface runoff and drainage from land-use activities.

In summary, the DCPs are intended to provide input data to the model developed for the river, enabling the model to be used as a valuable tool in formulating and implementing plans for the management of water resources and general environmental quality in a river basin.

CHAPTER VIII

CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

The sites for placement of DCP monitors in the length of the Warrior River from the confluence of the Locust and Mulberry Forks to downstream of the Oliver Lock and Dam have been selected and proposed as desirable locations for the assessment of water quality. Dissolved oxygen was selected as the parameter of primary importance and the selection of the DCP sites was based on observed and predicted locations of critical dissolved oxygen concentrations.

To implement the selection process, a mathematical modeling technique and supplementary computer program were developed for simulating dissolved oxygen profiles. The modeling technique, based on modifications of the original Streeter-Phelps Equation by Pyatt, was shown to predict values of dissolved oxygen concentration in the Warrior River which either agreed quite well with the observed values or could be explained on the basis of actual river conditions. Based primarily on dissolved oxygen criteria, the following five locations were recommended for placement of the five DCPs designated for use in the Alabama ERTS project.

(1) R. M. 385.0--below the confluence of Locust and Mulberry Forks

(2) R. M. 365.0--one-half mile below Bankhead Lock and Dam

(3) R. M. 346.5--one-half mile below Holt Lock and Dam

(4) R. M. 338.2--forebay of Oliver Lock and Dam

(5) R. M. 335.0--approximately three miles below Oliver Lock and Dam.

In addition to monitoring dissolved oxygen, it is anticipated that the DCPs will serve to monitor the other parameters of pH, conductivity, and temperature to provide information concerning basin-wide land use activities. The portability feature of the DCP will allow selection of other monitoring points for more detailed information concerning specific parameters and their relationship to a variety of activities.

The selection of the specific monitoring sites in this study was designed to provide a basin-wide management capability in which the data obtained at a relatively few locations could be employed to simulate and predict water quality over an extensive river basin area. The selection methods proposed in this study were also developed for general applicability in the selection of desirable DCP or conventional monitoring sites in any water basin.

8.2. Recommendations

During the course of this investigation several possibilities for further study, primarily concerned with operation of the DCPs after installation, have become evident:

(1) Provide for the collection of supplementary dissolved oxygen data at locations where differences were obtained between simulated and observed values, permitting modification of the model to obtain better agreement with actual observed conditions.

(2) During the periods between overflights of the ERTS satellite, allow the DCP to operate as a conventional automated monitor, transmitting data to a ground receiving station.

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(3) Include an addition to the DCP apparatus which would allow monitoring at different depths of the river, in order to evaluate the extent and effects of stratification in the reservoirs.

(4) Since the DCPs are portable, consider possible relocation of one or more of them in order to either expand or reduce the area of coverage, such as monitoring the quality of water in a clean stream (Mulberry Fork) in order to obtain base-line data on non-polluted conditions.

(5) Modify the DCP system for use as a network of conventional monitors after the ERTS satellite is removed from orbit.

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APPENDICES

APPENDIX I

INFORMATION RELATED TO USE OF THE COMPUTER PROGRAM

A1.1 General

The actual computer programming utilized in the implementation of the simulation technique developed during this study was performed in the PL/1 programming language.[42] The IBM 360/50 computer installation at The University of Alabama was employed in running the program.

The following sections contain information directly related to the program that would be useful to those interested in the programming method and, in addition, examples are given of output for the Warrior River during the summer of 1972.

A1.2 Flow Diagram

Shown in Figure 10 is a diagram indicating the general path of logic followed by the model in simulating the dissolved oxygen profile in a stream. It is intended to show the general nature of the process rather than to show the specific calculations made by the program.

A1.3 Program Output

The output from the program is printed in a tabular form, with a separate table being used for the compilation of data predicted for each month. Examples of output containing simulated data for the area of the Warrior Basin during the months of June, 1972, through September, 1972, are shown in Tables VII through X.

A1.4 Definition of Variables

Summarized below are definitions for the variables used as input data to the program:

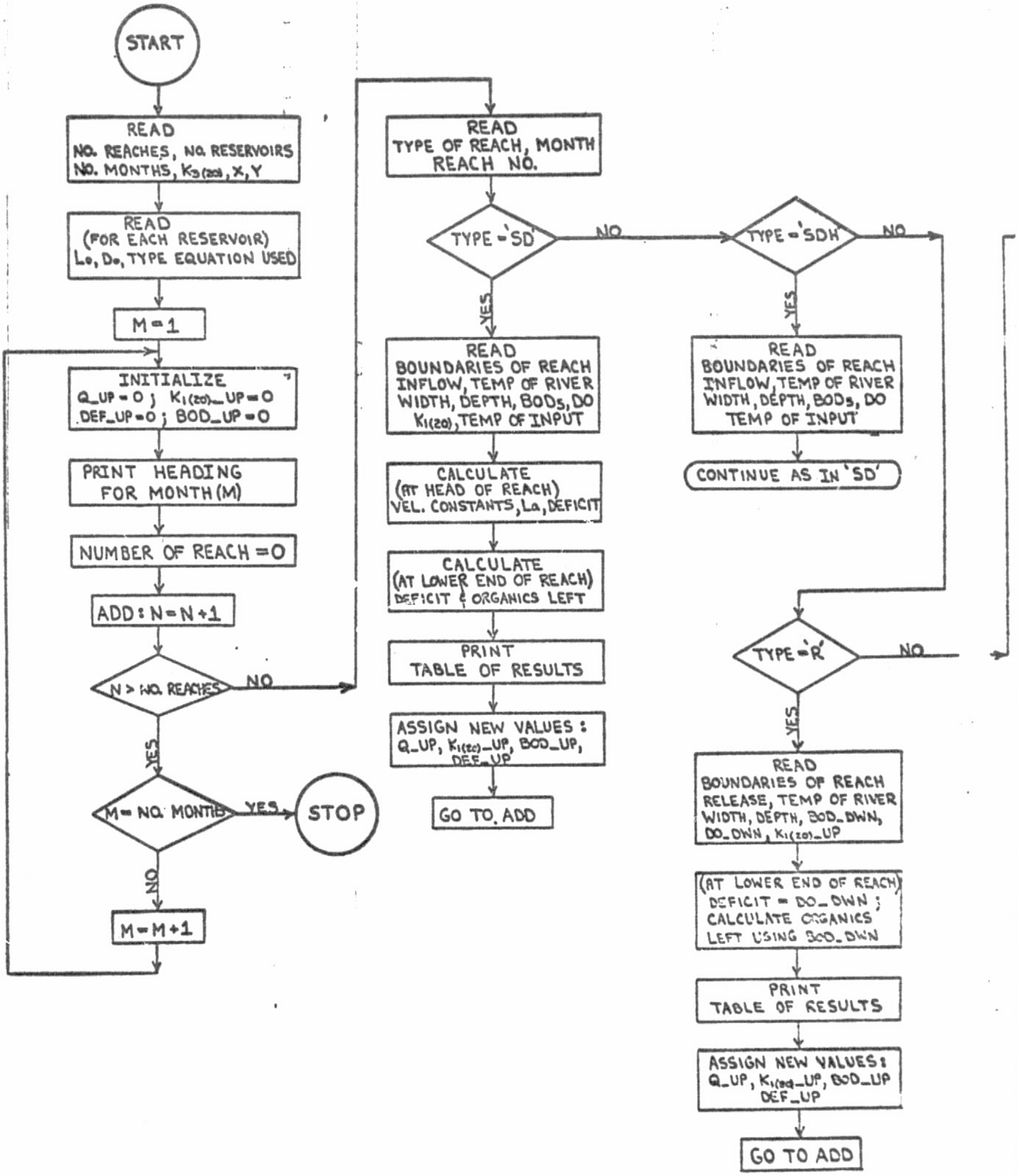

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TABLE VII

RESULTS OF SIMULATION OF WARRIOR RIVER (JUNE, 1972)

R. M. 385.0 TO R. M. 335.0

JUNE, 1972

REACH NO.	TYPE	UPSTREAM R. M.	DOWNSTREAM R. M.	FLOW (CFS)	RELEASE (CFS)	CSA (SQ. FT.)	TRAVEL TIME (DAYS)	K1 (BASE E)	K2 (BASE E)	DO UPPER END (PPM)	DO LOWER END (PPM)
1A	SD	385.00	382.00	1895.0		46153	4.58	0.190	0.014	6.0	5.6
2A	SD	382.00	367.50	1960.0		68294	44.30	0.196	0.006	5.6	5.0
3A	SDH	367.50	366.00	1970.0		78468	4.58	0.202	0.004	5.0	5.8
4A	R	366.00	365.40	1970.0	1970.0	92556	1.83	0.203	0.004	5.8	3.7
5A	N	365.40	361.50	1970.0		27787	3.40	0.176	0.046	3.7	5.1
6A	SDH	361.50	347.50	1985.0		56265	28.51	0.170	0.010	5.1	5.8
7A	R	347.50	346.90	1985.0	1880.0	86062	1.83	0.319	0.004	5.8	4.6
8A	N	346.90	346.30	1880.0		12294	0.24	0.193	0.178	4.6	4.5
9A	SD	346.30	345.70	1905.0		8587	0.16	0.192	0.137	4.5	4.6
10A	IHC	345.70	345.70	1904.3						4.6	4.6
10B	ID	345.70	345.20	1904.9		7761	0.12	0.198	0.180	4.6	4.6
10C	ID	345.20	344.40	1905.2		7761	0.20	0.196	0.180	4.6	4.5
11A	IHC	344.40	344.40	1903.4						4.5	4.5
11B	ID	344.40	344.39	1903.7		7191	0.00	0.195	0.180	4.5	4.5
11C	ID	344.39	343.70	1904.7		7191	0.16	0.195	0.180	4.5	4.5
12A	SDH	343.70	343.50	1974.7		7462	0.04	0.187	0.188	4.5	4.8
13A	ID	343.50	343.00	1980.1		7711	0.12	0.186	0.190	4.8	5.0
14A	IN	343.00	342.50	1952.2		9072	0.14	0.186	0.180	5.0	4.9
15A	ID	342.50	341.60	1970.7		7462	0.21	0.191	0.189	4.9	4.5
16A	SDH	341.60	338.41	1971.3		15443	1.62	0.190	0.053	4.5	3.4
17A	ID	338.41	338.39	1971.7		17589	0.01	0.187	0.030	3.4	3.4
18A	R	338.39	338.10	1971.7	2150.0	28912	0.29	0.125	0.020	3.4	6.6
19A	N	338.10	337.00	2150.0		9562	0.30	0.062	0.122	6.6	6.4
20A	IN	337.00	336.70	2149.3		7779	0.06	0.062	0.132	6.4	6.4
21A	ID	336.70	335.00	2150.0		6693	0.32	0.062	0.142	6.4	6.3

TABLE VIII

RESULTS OF SIMULATION OF WARRIOR RIVER (JULY, 1972)

R. M. 385.0 TO R. M. 335.0

JULY, 1972

REACH NO.	TYPE	UPSTREAM R. M.	DOWNSTREAM R. M.	FLOW (CFS)	RELEASE (CFS)	CSA (SQ. FT.)	TRAVEL TIME (DAYS)	K1 (BASE E)	K2 (BASE E)	DO UPPER END (PPM)	DO LOWER END (PPM)
1A	SD	385.00	382.00	2150.0		46153	4.58	0.198	0.014	6.7	5.[illegible]
2A	SD	382.00	367.50	2250.0		68294	29.53	0.208	0.006	5.6	4.7
3A	SDH	367.50	366.00	2260.0		78468	4.58	0.197	0.006	4.7	5.[illegible]
4A	R	366.00	365.40	2260.0	2260.0	92556	1.83	0.194	0.004	5.6	3.[illegible]
5A	N	365.40	361.50	2260.0		27787	2.97	0.167	0.047	3.4	4.[illegible]
6A	SDH	361.50	347.50	2285.0		56265	21.38	0.163	0.012	4.9	5.7
7A	R	347.50	346.90	2285.0	2270.0	86062	1.83	0.307	0.004	5.7	4.[illegible]
8A	N	346.90	346.30	2270.0		12294	0.20	0.202	0.198	4.3	4.[illegible]
9A	SD	346.30	345.70	2305.0		8587	0.14	0.201	0.153	4.1	4.2
10A	IHC	345.70	345.70	2304.3						4.2	4.2
10B	ID	345.70	345.20	2304.9		7761	0.10	0.205	0.200	4.2	4.0
10C	ID	345.20	344.40	2305.2		7761	0.16	0.204	0.200	4.0	3.7
11A	IHC	344.40	344.40	2303.4						3.7	3.7
11B	ID	344.40	344.39	2303.7		7191	0.00	0.202	0.203	3.7	3.7
11C	ID	344.39	343.70	2304.9		7191	0.13	0.202	0.203	3.7	3.9
12A	SDH	343.70	343.50	2414.9		7462	0.03	0.199	0.213	3.9	4.1
13A	ID	343.50	343.00	2420.3		7711	0.09	0.197	0.218	4.1	4.2
14A	ID	343.00	342.50	2392.4		9072	0.11	0.197	0.208	4.2	4.2
15A	ID	342.50	341.60	2410.9		7462	0.17	0.194	0.211	4.2	4.1
16A	SDH	341.60	338.41	2411.3		15443	1.29	0.193	0.061	4.1	3.1
17A	ID	338.41	338.39	2412.0		17589	0.00	0.202	0.033	3.1	3.1
18A	R	338.39	338.10	2412.0	2630.0	28912	0.22	0.135	0.022	3.1	5.7
19A	N	338.10	337.00	2630.0		9562	0.24	0.067	0.139	5.7	5.7
20A	ID	337.00	336.70	2629.3		7779	0.05	0.067	0.152	5.7	5.7
21A	ID	336.70	335.00	2630.0		6693	0.26	0.067	0.162	5.7	5.7

TABLE IX

RESULTS OF SIMULATION OF WARRIOR RIVER (AUGUST, 1972)

R. M. 385.0 TO R. M. 335.0

AUGUST, 1972

REACH NO.	TYPE	UPSTREAM R. M.	DOWNSTREAM R. M.	FLOW (CFS)	RELEASE (CFS)	CSA (SQ. FT.)	TRAVEL TIME (DAYS)	K1 (BASE E)	K2 (BASE E)	DO UPPER END (PPM)	DO LOWER END (PPM)
1A	SD	385.00	382.00	1615.0		46153	6.11	0.218	0.012	6.6	6.2
2A	SD	382.00	367.50	1715.0		68294	44.30	0.218	0.007	6.2	6.1
3A	SDH	367.50	366.00	1730.0		78468	4.58	0.206	0.004	6.1	6.6
4A	R	366.00	365.40	1730.0	1730.0	92556	3.66	0.209	0.002	6.6	5.1
5A	N	365.40	361.50	1730.0		27787	3.97	0.183	0.044	5.1	5.6
6A	SDH	361.50	347.50	1740.0		56265	28.51	0.188	0.010	5.6	5.9
7A	R	347.50	346.90	1740.0	1730.0	86062	1.83	0.328	0.004	5.9	3.9
8A	N	346.90	346.30	1730.0		12294	0.26	0.207	0.177	3.9	3.6
9A	SD	346.30	345.70	1755.0		8587	0.18	0.206	0.133	3.6	3.6
10A	INC	345.70	345.70	1754.3						3.6	3.6
10B	ID	345.70	345.20	1754.9		7761	0.13	0.210	0.176	3.6	3.6
10C	ID	345.20	344.40	1755.2		7761	0.22	0.208	0.176	3.6	3.5
11A	INC	344.40	344.40	1753.4						3.5	3.3
11B	ID	344.40	344.39	1753.7		7191	0.00	0.207	0.176	3.3	3.3
11C	ID	344.39	343.70	1754.9		7191	0.17	0.207	0.176	3.3	3.3
12A	SDH	343.70	343.50	1864.9		7462	0.05	0.194	0.184	3.3	3.2
13A	ID	343.50	343.00	1870.3		7711	0.12	0.193	0.189	3.2	3.6
14A	IN	343.00	342.50	1842.4		9072	0.15	0.193	0.182	3.6	3.8
15A	ID	342.50	341.60	1860.9		7462	0.22	0.194	0.184	3.8	3.7
16A	SDH	341.60	338.41	1861.4		15443	1.62	0.193	0.054	3.7	3.6
17A	ID	338.41	338.39	1861.9		17589	0.01	0.193	0.028	3.6	2.4
18A	R	338.39	338.10	1861.9	2000.0	28912	0.29	0.131	0.020	2.4	2.4
19A	N	338.10	337.00	2000.0		9562	0.33	0.065	0.118	2.4	5.4
20A	IN	337.00	336.70	1999.3		7779	0.07	0.065	0.130	5.4	5.4
21A	ID	336.70	335.00	2000.0		6693	0.35	0.065	0.137	5.4	5.5

TABLE X

RESULTS OF SIMULATION OF WARRIOR RIVER (SEPTEMBER, 1972)

R. M. 385.0 TO R. M. 335.0

SEPTEMBER, 1972

REACH NO.	TYPE	UPSTREAM R. M.	DOWNSTREAM R. M.	FLOW (CFS)	RELEASE (CFS)	CSA (SQ. FT.)	TRAVEL TIME (DAYS)	K1 (BASE E)	K2 (BASE E)	DO UPPER END (PPM)	DO LOWER END (PPM)
1A	SD	385.00	382.00	1975.0		46153	4.58	0.199	0.014	5.9	5.2
2A	SD	382.00	367.50	2100.0		68294	29.53	0.203	0.006	5.2	5.0
3A	SDH	367.50	366.00	2110.0		78468	4.58	0.206	0.004	5.0	5.7
4A	R	366.00	365.40	2110.0	2110.0	92556	1.83	0.207	0.004	5.7	3.0
5A	N	365.40	361.50	2110.0		27787	3.40	0.180	0.046	3.0	4.4
6A	SDH	361.50	347.50	2125.0		56265	28.51	0.183	0.010	4.4	5.0
7A	R	347.50	346.90	2125.0	2040.0	86062	1.83	0.314	0.004	5.0	4.4
8A	N	346.90	346.30	2040.0		12294	0.22	0.207	0.190	4.4	4.2
9A	SD	346.30	345.70	2055.0		8587	0.15	0.206	0.143	4.2	4.2
10A	IWC	345.70	345.70	2054.3						4.2	4.2
10B	ID	345.70	345.20	2054.9		7761	0.11	0.204	0.190	4.2	4.1
10C	ID	345.20	344.40	2055.2		7761	0.18	0.203	0.190	4.1	4.0
11A	IWC	344.40	344.40	2053.4						4.0	4.0
11B	ID	344.40	344.39	2053.7		7191	0.00	0.201	0.190	4.0	4.0
11C	ID	344.39	343.70	2054.8		7191	0.15	0.201	0.190	4.0	4.0
12A	SDH	343.70	343.50	2194.8		7462	0.04	0.187	0.200	4.0	4.4
13A	ID	343.50	343.00	2200.2		7711	0.10	0.186	0.202	4.4	4.5
14A	ID	343.00	342.50	2172.3		9072	0.13	0.186	0.192	4.5	4.4
15A	ID	342.50	341.60	2190.8		7462	0.18	0.187	0.200	4.4	4.4
16A	SDH	341.60	338.41	2191.4		15443	1.39	0.186	0.058	4.4	3.2
17A	ID	338.41	338.39	2192.1		17589	0.01	0.186	0.030	3.2	3.2
18A	R	338.39	338.10	2192.1	2320.0	28912	0.25	0.128	0.022	3.2	6.7
19A	N	338.10	337.00	2320.0		9562	0.28	0.065	0.130	6.7	6.6
20A	ID	337.00	336.70	2319.3		7779	0.06	0.065	0.140	6.6	6.6
21A	ID	336.70	335.00	2320.0		6693	0.30	0.065	0.150	6.6	6.5

NOT_REACHES	total number of reaches into which the river is divided.
NOR	number of reservoirs on the stretch of the river being modeled.
NOM	number of months for which simulation is to be performed.
K320_E	deoxygenation constant due to bottom deposits at 20 °C. (base e), $days^{-1}$.
X	deoxygenation error term, $days^{-1}$.
Y	reaeration error term, $days^{-1}$.
LAI(S)	concentration of organic matter in reservoir S before waste inputs from upstream are added, mg/l.
DEFI(S)	concentration of dissolved oxygen in reservoir S before waste inputs from upstream are added, mg/l.
FORM(S)	type of equations used for predicting DO in reservoir S, Streeter-Phelps or modification by Pyatt for reservoirs.
TYPE	category of input for the reach in question--SD, SDH, R, N, ID, IW, IWC.
REACH	number of the reach.
MONTH	month for which the data was taken.
UPSTM	upstream boundary of the reach, river miles.
DWNSTM	downstream boundary of the reach, river miles.
DISCH	discharge of a tributary, cfs.
DIS_I	discharge of an industry, mgd.
WTHDR	amount of withdrawal by an industry, mgd.
REL	amount of flow released from a dam, cfs.
RIVTEMP	temperature of the river water, °C.
INTEMP	temperature of water in the input to a reach, °C.
WIDTH	surface width of the river, ft.
DEPTH	mean depth of the river in a reach, ft.

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BOD5	BOD_5 of the input waste at 20 °C., mg/l.
BOD_DWN	BOD_5 of the river water (20 °C.) immediately below a dam, mg/l.
DO	dissolved oxygen concentration in the input to a reach, mg/l.
DO_DWN	dissolved oxygen concentration of the river water immediately below a dam, mg/l.
K120_10	deoxygenation constant at 20 °C. for the river water or input to a reach (base 10), $days^{-1}$.

A1.5 Listing of the Program Statements

On the following pages the actual PL/1 statements of the program are shown. It is hoped that any potential user employing the information provided in the preceding sections of Appendix I, in addition to these program statements, could either utilize the program intact or easily adapt the programming to fit his particular needs.

```
START: PROC OPTIONS(MAIN);
/*****************************************************************/
/*****************************************************************/
/*****************************************************************/
/** THIS PROGRAM SIMULATES DISSOLVED OXYGEN IN A RIVER ENVIRONMENT ***/
/*****************************************************************/
/*****************************************************************/
DCL ZILCH CHAR(1);
DCL (EXP1,EXP2) FIXED DECIMAL(5,3);
DCL FORM(4) CHAR(3) VARYING;
DCL CNT FIXED DECIMAL(3);
DCL CAPACITY(16) FIXED DECIMAL(5,0);
DCL (Q_IN(16),Q_OUT(16)) FIXED DECIMAL(6,1);
DCL (X,Y,WCHK) FIXED DECIMAL(5,3);
DCL (TYPE,REACH) CHAR(3) VARYING;
DCL (MO(4),MONTH) CHAR(9) VARYING;
DCL DATE(4) CHAR(15) VARYING;
DCL (TOT_REACHES,NOM,NOR,M,N,S,T) FIXED DECIMAL(2);
DCL (SLOPE,INTERCEPT) FIXED DECIMAL(6,4);
DCL (C,D,E,F,G,H,I,J,K,L,O,P,Q) FIXED DECIMAL(7,4);
DCL (BOD_UP,BOD5,LA_IN,LA,L_DWN,LA_INIT,BOD5_INIT,BOD_DWN,LA20,
   LAI(4)) FIXED DECIMAL(6,1);
DCL (RIVTEMP,INTEMP,DO,DO_UP,DO_DWN,DOSATR,DOSATW,DEF_UP,DEF_DWN,
   DEF_IN,DEF,DEF_INIT,DO_INIT,DEFI(4)) FIXED DECIMAL(4,1);
    DCL (K120_UP,K120_10,K120_F,K220_10,K220_E,K120_MIX,K1,K2,K3,
   K320_E,W,Z,A,B) FIXED DECIMAL(5,3);
DCL (Q_UP,DISCH,WIDTH,DEPTH,FLOW,REL) FIXED DECIMAL(6,1);
DCL (UPSTM,DWNSTM,DIS_I,WTHDR) FIXED DECIMAL(6,2);
DCL (LENGTH,CSA) FIXED DECIMAL(6);
DCL VEL FIXED DECIMAL(4,2);
DCL TIME FIXED DECIMAL(5,2);
DCL VOLUME FIXED DECIMAL(10);
MO(1)='JUNE';
MO(2)='JULY';
MO(3)='AUGUST';
MO(4)='SEPTEMBER';
GET EDIT(TOT_REACHES,NOR,NOM,K320_E,X,Y,ZILCH) (COL(1),F(2),COL(21),
   F(2),COL(31),F(2),COL(41),F(5,3),COL(51),F(5,3),COL(61),F(5,3),
   X(14),A(1));
DO S = 1 TO NOR;
GET EDIT(LAI(S),DEFI(S),FORM(S),ZILCH) (COL(1),F(5,1),COL(10),F(4,1),
   COL(20),A(3),X(57),A(1));
END;
M=1;
RESET: Q_UP = 0.0;
K120_UP=0.0;
DEF_UP=0.0;
BOD_UP=0.0;
PUT PAGE;
PUT SKIP(13) EDIT('SUMMARY FOR WARRIOR RIVER') (COL(48),A);
PUT SKIP(2) EDIT('R. M. 385.0  TO  R. M. 335.0') (COL(47),A);
DATE(M)=MO(M) || ', 1972';
PUT SKIP(2) EDIT(DATE(M)) (COL(54),A);
PUT SKIP(3) EDIT('REACH','TYPE','UPSTREAM','DOWNSTREAM','FLOW',
   'RELEASE','CSA','TRAVEL','K1','K2','DO','DO') (COL(1),A,COL(8),A,
   COL(15),A,COL(25),A,COL(38),A,COL(46),A,COL(59),A,COL(68),A,
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```
   COL(80),A,COL(91),A,COL(102),A,COL(114),A);
PUT SKIP EDIT('NO.','R. M.','R. M.','(CFS)','(CFS)','(SQ. FT.)','TIME',
   '(BASE E)','(BASE E)','UPPER END','LOWER END') (COL(2),A,COL(17),A,
   COL(28),A,COL(38),A,COL(47),A,COL(56),A,COL(69),A,COL(77),A,
   COL(89),A,COL(99),A,COL(111),A);
PUT SKIP EDIT('(DAYS)','(PPM)','(PPM)') (COL(68),A,COL(101),A,
   COL(113),A);
PUT SKIP(2) EDIT(' ') (COL(2),A);
N = 0;
T = 0;
ADD: N=N+1;
IF N = 1 THEN DO;
T = T + 1;
LA_INIT = LA'(T);
DEF_INIT = DEFI(T);
END;
ELSE GO TO CHECK;
CHECK: IF N > TOT_REACHES THEN DO;
IF M=NOM THEN GO TO LAST;
ELSE GO TO NEXT;
NEXT: M=M+1;
GO TO RESET;  END;
ELSE DO;
READ: GET EDIT(TYPE,REACH,MONTH) (COL(1),A(3),COL(6),A(3),COL(11),
   A(9));  END;
/*****************************************************************************/
/*****************************************************************************/
/************** POLLUTED STREAM DISCHARGING INTO RIVER **************/
/*****************************************************************************/
/*****************************************************************************/
IF TYPE='SD' THEN DO;
STREAM:GET EDIT(UPSTM,DWNSTM,DISCH,RIVTEMP,WIDTH,DEPTH)(COL(25),F(6,2),
   COL(35),F(6,2),COL(45),F(6,1),COL(57),F(4,1),COL(65),F(6,1),
   COL(75),F(6,1));
GET EDIT(BODS,DO,K120_10,INTEMP,ZILCH) (COL(25),F(6,1),COL(37),F(4,1),
   COL(46),F(5,3),COL(57),F(4,1),X(19),A(1));
IF N=1 THEN DO_UP=DO;
ELSE DO_UP=DOSATR - DEF_UP;
DOSATW = 14.65 - 0.41*INTEMP + 0.008*INTEMP**2 - 0.00008*INTEMP**3;
LENGTH = (UPSTM - DWNSTM) * 5280.0;
CSA = 0.75 * WIDTH * DEPTH;
VOLUME = CSA * LENGTH;
FLOW = Q_UP + DISCH;
VEL = FLOW/CSA;
TIME = (LENGTH/VEL) / 86400.0;
K120_E = K120_10 * 2.303;
K120_MIX = ((K120_UP*Q_UP) + (K120_E*DISCH)) / FLOW;
K220_10 = (12.90 * VEL**0.5) / (DEPTH**1.5);
K220_E = K220_10 * 2.303;
K1 = K120_MIX * 1.047**(RIVTEMP-20.0);
K2 = K220_E * 1.0159**(RIVTEMP-20.0);
K3 = K320_E * 1.047**(RIVTEMP-20.0);
LA_IN = BODS / (1.0-1.0/(2.71**(5*K120_E)));
LA20 = ((BOD_UP * Q_UP) + (LA_IN * DISCH))/FLOW;
LA = LA20 * (0.02 * RIVTEMP + 0.60);
```

```
DEF_IN = DOSATW - DO;
DOSATR = 14.65 - 0.41*RIVTEMP + 0.008*RIVTEMP**2 - 0.00008*RIVTEMP**3;
DEF = (((DOSATR-DO_UP) * Q_UP) + (DEF_IN * DISCH)) / FLOW;
IF FORM(T) = 'RES' THEN DO;
W = FLOW * (86400.0/VOLUME);
IF N=1 THEN Z = DISCH * (86400.0/VOLUME);
ELSE Z = Q_UP * (86400.0/VOLUME);
A = K1 + K3 + W;
B = K2 + W;
BOD_SD:  L_DWN = LA_INIT*(1.0/(2.71**(A*TIME))) + ((Z*LA)/A) *
   (1.0-1.0/(2.71**(A*TIME)));
C = DEF_INIT - (Z*DEF)/B;
D = K1 / (A-B);
E = LA_INIT - (Z*LA)/B;
F = 1.0/(2.71**(B*TIME));
G = K1/(B-A);
H = LA_INIT - (Z*LA)/A;
I = 1.0/(2.71**(A*TIME));
J = Z/B;
K = DEF + (K1*LA)/A;
DEF_SD:  DEF_DWN = (C+(D*E))*F + (G*H)*I + (J*K);
END;
ELSE DO;
L_DWN = (LA - X/K1) * (1.0/(2.71**(K1*TIME))) + X/K1;
EXP1 = 1.0 / (2.71**(K1*TIME));
EXP2 = 1.0 / (2.71**(K2*TIME));
IF K2 = K1 THEN DO;
L = K1 * TIME;
O = (LA-X)/K1;
P = (X+Y)/K1;
DEF_DWN = (L*O + DEF + P) * EXP1 - P;   END;
ELSE DO;
DEF_DWN = ((K1*LA - X) / (K2-K1)) * (EXP1 - EXP2) + ((X+Y)/K2) *
   (1.0-1.0/(2.71**(K2*TIME))) + DEF*(1.0/(2.71**(K2*TIME)));   END;
END;
IF LENGTH < (0.1*5280.0) THEN DO_DWN = DO_UP;
ELSE DO_DWN = DOSATR - DEF_DWN;
PRINT_SD: PUT SKIP EDIT(REACH,TYPE,UPSTM,DWNSTM,FLOW,CSA,TIME,K1,K2,
   DO_UP,DO_DWN) (COL(2),A(3),COL(9),A(3),COL(17),F(6,2),COL(28),
   F(6,2),COL(37),F(6,1),COL(58),F(6),COL(68),F(5,2),COL(79),F(5,3),
   COL(90),F(5,3),COL(101),F(4,1),COL(113),F(4,1));
Q_UP = FLOW;
BOD_UP = L_DWN / (0.02 * RIVTEMP + 0.6);
DEF_UP = DOSATR - DO_DWN;
K120_UP = K120_MIX;
GO TO ADD;
END;
/*************************************************************************/
/*************************************************************************/
/*************** CLEAN STREAM DISCHARGING INTO RIVER ***************/
/*************************************************************************/
/*************************************************************************/
ELSE IF TYPE = 'SDH' THEN DO;
STREAM_CLEAN: GET EDIT(UPSTM,DWNSTM,DISCH,RIVTEMP,WIDTH,DEPTH)
   (COL(25),F(6,2),COL(35),F(6,2),COL(45),F(6,1),COL(57),F(4,1),
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   COL(65),F(6,1),COL(75),F(6,1));
GET EDIT(DO,INTEMP,ZILCH)(COL(37),F(4,1),COL(57),F(4,1),X(19),A(1));
IF N=1 THEN DO_UP=DO;
ELSE DO_UP = DOSATR - DEF_UP;
DOSATW = 14.65 - 0.41*INTEMP + 0.008*INTEMP**2 - 0.00008*RIVTEMP**3;
LENGTH = (UPSTM - DWNSTM) * 5280.0;
CSA = 0.75 * WIDTH * DEPTH;
VOLUME = CSA * LENGTH;
FLOW = Q_UP + DISCH;
VEL = FLOW / CSA;
TIME = (LENGTH/VEL) / 86400.0;
K120_MIX = (K120_UP * Q_UP) / FLOW;
K220_10 = (12.90 * VEL**0.5) / (DEPTH**1.5);
K220_E = K220_10 * 2.303;
K1 = K120_MIX * 1.047**(RIVTEMP-20.0);
K2 = K220_E * 1.0159**(RIVTEMP-20.0);
K3 = K320_E * 1.047**(RIVTEMP-20.0);
LA20 = (BOD_UP * Q_UP) / FLOW;
LA = LA20 * (0.02 * RIVTEMP + 0.60);
DEF_IN = DOSATW - DO;
DOSATR = 14.65 - 0.41*RIVTEMP + 0.008*RIVTEMP**2 - 0.00008*RIVTEMP**3;
DEF = (((DOSATR - DO_UP) * Q_UP) + (DEF_IN * DISCH)) / FLOW;
IF FORM(T) = 'RES' THEN DO;
W = FLOW * (86400.0/VOLUME);
IF N=1 THEN Z = DISCH * (86400.0/VOLUME);
ELSE Z = Q_UP * (86400.0/VOLUME);
A = K1 + K3 + W;
B = K2 + W;
BOD_SDH: L_DWN = LA_INIT*(1.0/(2.71**(A*TIME))) + ((Z*LA)/A) *
   (1.0-1.0/(2.71**(A*TIME)));
C = DEF_INIT - (Z*DEF)/B;
D = K1 / (A-B);
E = LA_INIT - (Z*LA)/B;
F = 1.0/(2.71**(B*TIME));
G = K1/(B-A);
H = LA_INIT - (Z*LA)/A;
I = 1.0/(2.71**(A*TIME));
J = Z/B;
K = DEF + (K1*LA)/A;
DEF_SDH: DEF_DWN = (C+(D*E))*F + (G*H)*I + (J*K);
END;
ELSE DO;
L_DWN = (LA - X/K1) * (1.0/(2.71**(K1*TIME))) + X/K1;
EXP1 = 1.0 / (2.71**(K1*TIME));
EXP2 = 1.0 / (2.71**(K2*TIME));
IF K2 = K1 THEN DO;
L = K1 * TIME;
O = (LA-X)/K1;
P = (X+Y)/K1;
DEF_DWN = (L*O + DEF + P) * EXP1 - P;   END;
ELSE DO;
DEF_DWN = ((K1*LA - X) / (K2-K1)) * (EXP1 - EXP2) + ((X+Y)/K2) *
   (1.0-1.0/(2.71**(K2*TIME))) + DEF*(1.0/(2.71**(K2*TIME)));   END;
END;
IF LENGTH < (0.1*5280.0) THEN DO_DWN = DO_UP;
```

```
ELSE DO_DWN = DOSATR - DEF_DWN;
PRINT_SDH: PUT SKIP EDIT(REACH,TYPE,UPSTM,DWNSTM,FLOW,CSA,TIME,K1,K2,
   DO_UP,DO_DWN) (COL(2),A(3),COL(9),A(3),COL(17),F(6,2),COL(28),
   F(6,2),COL(37),F(6,1),COL(58),F(6),COL(68),F(5,2),COL(79),F(5,3),
   COL(90),F(5,3),COL(101),F(4,1),COL(113),F(4,1));
Q_UP = FLOW;
BOD_UP = L_DWN / (0.02 * RIVTEMP + 0.6);
DEF_UP = DOSATR - DO_DWN;
K120_UP = K120_MIX;
GO TO ADD;
END;
/*******************************************************************/
/*******************************************************************/
/**** REACH CONTAINING A DAM OR OTHER FLOW CONTROLLING STRUCTURE ****/
/*******************************************************************/
/*******************************************************************/
ELSE IF TYPE= 'R' THEN DO;
RESERVOIR: GET EDIT(UPSTM,DWNSTM,REL,RIVTEMP,WIDTH,DEPTH) (COL(25),
   F(6,2),COL(35),F(6,2),COL(45),F(6,1),COL(57),F(4,1),COL(65),F(6,1),
   COL(75),F(6,1));
GET EDIT(BOD_DWN,DO_DWN,K120_10,ZILCH) (COL(25),F(6,1),COL(37),F(4,1),
   COL(56),F(5,3),X(19),A(1));
IF N=1 THEN DO_UP = DO;
ELSE DO_UP = DOSATR - DEF_UP;
LENGTH = (UPSTM - DWNSTM) * 5280.0;
CSA = 0.75 * WIDTH * DEPTH;
VOLUME = CSA * LENGTH;
FLOW = Q_UP;
VEL = FLOW / CSA;
TIME = (LENGTH/VEL) / 86400.0;
K120_E = K120_10 * 2.303;
K120_MIX = K120_E;
K220_10 = (12.90 * VEL**0.5) / (DEPTH**1.5);
K220_E = K220_10 * 2.303;
K1 = K120_MIX * 1.047**(RIVTEMP-20.0);
K2 = K220_E * 1.0159**(RIVTEMP-20.0);
K3 = K320_E * 1.047**(RIVTEMP-20.0);
LA20 = BOD_UP;
LA = LA20 * (0.02 * RIVTEMP + 0.60);
DOSATR = 14.65 - 0.41*RIVTEMP + 0.008*RIVTEMP**2 - 0.00008*RIVTEMP**3;
DEF = DOSATR - DO_UP;
DEF_DWN = DOSATR - DO_DWN;
PRINT_R:PUT SKIP EDIT (REACH, TYPE, UPSTM, DWNSTM, FLOW, REL, CSA, TIME
   , K1, K2, DO_UP, DO_DWN) (COL(2),A(3), COL(9), A(3), COL(17), F(6,2)
   , COL(28), F(6,2), COL(37), F(6,1), COL(47), F(6,1), COL(58), F(6),
   COL(68), F(5,2), COL(79), F(5,3), COL(90), F(5,3),COL(101), F(4,1),
   COL(113),F(4,1));
Q_UP=REL;
DEF_UP=DEF_DWN;
K120_UP=K120_MIX;
GO TO ADD;
END;
/*******************************************************************/
/*******************************************************************/
/*************** REACH CONTAINING NO INPUT TO RIVER ****************/
```

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/**************** OCCURS BELOW REACH CONTAINING A DAM ****************/
/*********************************************************************/
/*********************************************************************/
ELSE IF TYPE = 'N' THEN DO;
T = T + 1;
LA_INIT = LAI(T);
DEF_INIT = DEFI(T);
NO_INPUT: GET EDIT (UPSTM, DWNSTM, DISCH, RIVTEMP, WIDTH, DEPTH) (COL(
   25), F(6,2), COL(35), F(6,2), COL(45), F(6,1), COL(57), F(4,1), COL(
   65), F(6,1), COL(75), F(6,1));
GET EDIT(K120_10,ZILCH)(COL(26), F(5,3),X(49),A(1));
IF N=1 THEN DO_UP=DO;
ELSE DO_UP=DOSATR-DEF_UP;
LENGTH=(UPSTM-DWNSTM)*5280.0;
CSA = 0.75 * WIDTH * DEPTH;
VOLUME = CSA * LENGTH;
FLOW=Q_UP+DISCH;
VEL=FLOW/CSA;
TIME=(LENGTH/VEL)/86400.0;
K120_E=K120_10*2.303;
K120_MIX=K120_E;
K220_10=(12.90*VEL**0.5)/(DEPTH**1.5);
K220_E=K220_10*2.303;
K1=K120_MIX*1.047**(RIVTEMP-20.0);
K2=K220_E*1.0159**(RIVTEMP-20.0);
K3 = K320_E * 1.047**(RIVTEMP-20.0);
LA20 = BOD_DWN / (1.0-1.0/(2.71**(5*K120_E)));
LA = LA20 * (0.02 * RIVTEMP + 0.60);
DOSATR = 14.65 - 0.41*RIVTEMP + 0.008*RIVTEMP**2 - 0.00008*RIVTEMP**3;
DEF=DOSATR-DO_UP;
IF FORM(T) = 'RFS' THEN DO;
W = FLOW * (86400.0/VOLUME);
Z = Q_UP * (86400.0/VOLUME);
A = K1 + K3 + W;
B = K2 + W;
BOD_N:   L_DWN = LA_INIT*(1.0/(2.71**(A*TIME))) + ((Z*LA)/A) *
   (1.0-1.0/(2.71**(A*TIME)));
C = DEF_INIT - (Z*DEF)/B;
D = K1 / (A-B);
E = LA_INIT - (Z*LA)/B;
F = 1.0/(2.71**(B*TIME));
G = K1/(B-A);
H = LA_INIT - (Z*LA)/A;
I = 1.0/(2.71**(A*TIME));
J = Z/B;
K = DEF + (K1*LA)/A;
DEF_N:   DEF_DWN = (C+(D*E))*F + (G*H)*I + (J*K);
END;
ELSE DO;
L_DWN = (LA - X/K1) * (1.0/(2.71**(K1*TIME))) + X/K1;
EXP1 = 1.0 / (2.71**(K1*TIME));
EXP2 = 1.0 / (2.71**(K2*TIME));
IF K2 = K1 THEN DO;
L = K1 * TIME;
O = (LA-X)/K1;
```

```
P = (X+Y)/K1;
DEF_DWN = (L*D + DEF + P) * EXP1 - P;   END;
ELSE DO;
DEF_DWN = ((K1*LA - X) / (K2-K1)) * (EXP1 - EXP2) + ((X+Y)/K2) *
   (1.0-1.0/(2.71**(K2*TIME))) + DEF*(1.0/(2.71**(K2*TIME)));   END;
END;
IF LENGTH < (0.1*5280.0) THEN DO_DWN = DO_UP;
ELSE DO_DWN = DOSATR - DEF_DWN;
PRINT_N:PUT SKIP EDIT(REACH,TYPE,UPSTM,DWNSTM,FLOW,CSA,TIME,K1,K2,DO_UP
   ,DO_DWN)(COL(2),A(3),COL(9),A(3),COL(17),F(6,2),COL(28),F(6,2),
   COL(37),F(6,1),COL(58),F(6),COL(68),F(5,2),COL(79),F(5,3),COL(90),
   F(5,3),COL(101),F(4,1),COL(113),F(4,1));
Q_UP=FLOW;
BOD_UP = L_DWN / (0.02 * RIVTEMP + 0.6);
DEF_UP = DOSATR - DO_DWN;
K120_UP=K120_MIX;
GO TO ADD;
END;
/*********************************************************************/
/*********************************************************************/
/*************** INDUSTRY DISCHARGING WASTE INTO RIVER **************/
/*********************************************************************/
/*********************************************************************/
ELSE IF TYPE='ID' THEN DO;
IND_DIS:GET EDIT(UPSTM,DWNSTM,DIS_I,RIVTEMP,WIDTH,DEPTH)(COL(25),F(6,2)
   ,COL(35),F(6,2),COL(45),F(6,2),COL(57),F(4,1),COL(65),F(6,1),
   COL(75),F(6,1));
GET EDIT(BOD5,DO,K120_10,INTEMP,ZILCH)(COL(25),F(6,1),COL(37),F(4,1),
   COL(46),F(5,3), COL(57),F(4,1),X(19),A(1));
IF N=1 THEN DO_UP=DO;
ELSE DO_UP=DOSATR-DEF_UP;
DOSATW = 14.65 - 0.41*INTEMP + 0.008*INTEMP**2 - 0.00008*INTEMP**3;
LENGTH=(UPSTM-DWNSTM)*5280.0;
CSA = 0.75 * WIDTH * DEPTH;
VOLUME = CSA * LENGTH;
FLOW=Q_UP+(DIS_I*1.545);
VEL=FLOW/CSA;
TIME=(LENGTH/VEL)/86400.0;
K120_E=K120_10*2.303;
K120_MIX=((K120_UP*Q_UP)+(K120_E*(DIS_I*1.545)))/FLOW;
K220_10=(12.90*VEL**0.5)/(DEPTH**1.5);
K220_E=K220_10*2.303;
K1=K120_MIX*1.047**(RIVTEMP-20.0);
K2=K220_E*1.0159**(RIVTEMP-20.0);
K3 = K320_E * 1.047**(RIVTEMP-20.0);
LA_IN=BOD5/(1.0-1.0/(2.71**(5*K120_E)));
LA20 = ((BOD_UP*Q_UP) + (LA_IN * DIS_I)) / FLOW;
LA = LA20 * (0.02 * RIVTEMP + 0.60);
DEF_IN=DOSATW-DO;
DOSATR = 14.65 - 0.41*RIVTEMP + 0.008*RIVTEMP**2 - 0.00008*RIVTEMP**3;
DEF=(((DOSATR-DO_UP)*Q_UP)+(DEF_IN*DIS_I))/FLOW;
IF FORM(T) = 'RES' THEN DO;
W = FLOW * (86400.0/VOLUME);
Z = Q_UP * (86400.0/VOLUME);
A = K1 + K3 + W;
```

```
B = K2 + W;
ADO_ID:  L_DWN = LA_INIT*(1.0/(2.71**(A*TIME))) + ((Z*LA)/A) *
   (1.0-1.0/(2.71**(A*TIME)));
C = DEF_INIT - (Z*DEF)/B;
D = K1 / (A-B);
E = LA_INIT - (Z*LA)/B;
F = 1.0/(2.71**(B*TIME));
G = K1/(B-A);
H = LA_INIT - (Z*LA)/A;
I = 1.0/(2.71**(A*TIME));
J = Z/B;
K = DEF + (K1*LA)/A;
DEF_ID:  DEF_DWN = (C+(D*E))*F + (G*H)*I + (J*K);
END;
ELSE DO;
L_DWN = (LA - X/K1) * (1.0/(2.71**(K1*TIME))) + X/K1;
EXP1 = 1.0 / (2.71**(K1*TIME));
EXP2 = 1.0 / (2.71**(K2*TIME));
IF K2 = K1 THEN DO;
L = K1 * TIME;
O = (LA-X)/K1;
P = (X+Y)/K1;
DEF_DWN = (L*O + DEF + P) * EXP1 - P;   END;
ELSE DO;
DEF_DWN = ((K1*LA - X) / (K2-K1)) * (EXP1 - EXP2) + ((X+Y)/K2) *
   (1.0-1.0/(2.71**(K2*TIME))) + DEF*(1.0/(2.71**(K2*TIME)));   END;
END;
IF LENGTH < (0.1*5280.0) THEN DO_DWN = DO_UP;
ELSE DO_DWN = DOSATR - DEF_DWN;
PRINT_ID:PUT SKIP EDIT(REACH,TYPE,UPSTM,DWNSTM,FLOW,CSA,TIME,K1,K2,
   DO_UP,DO_DWN)(COL(2),A(3),COL(9),A(3),COL(17),F(6,2),COL(28),F(6,2),
   COL(37),F(6,1),COL(58),F(6),COL(68),F(5,2),COL(79),F(5,3),COL(90),
   F(5,3),COL(101),F(4,1),COL(113),F(4,1));
Q_UP=FLOW;
BOD_UP = L_DWN / (0.02 * RIVTEMP + 0.6);
DEF_UP = DOSATR - DO_DWN;
K120_UP=K120_MIX;
GO TO ADD;
END;
/***********************************************************************/
/***********************************************************************/
/*************** INDUSTRY WITHDRAWING WATER FROM RIVER **************/
/***********************************************************************/
/***********************************************************************/
ELSE IF TYPE='IW' THEN DO;
IND_WTHDRWL:GET EDIT(UPSTM,DWNSTM,WTHDR,RIVTEMP,WIDTH,DEPTH)(COL(25),
   F(6,2),COL(35),F(6,2),COL(45),F(6,2),COL(57),F(4,1),COL(65),F(6,1),
   COL(75),F(6,1));
IF N=1 THEN DO_UP=DO;
ELSE DO_UP=DOSATR-DEF_UP;
LENGTH=(UPSTM-DWNSTM)*5280.0;
CSA = 0.75 * WIDTH * DEPTH;
VOLUME = CSA * LENGTH;
FLOW=Q_UP+(WTHDR*1.545);
VEL=FLOW/CSA;
```

```
TIME=(LENGTH/VEL)/86400.0;
K120_MIX=K120_UP;
K220_10=(12.90*VEL**0.5)/(DEPTH**1.5);
K220_E = K220_10 * 2.303;
K1=K120_MIX*1.047**(RIVTEMP-20.0);
K2=K220_E*1.0159**(RIVTEMP-20.0);
K3 = K320_E * 1.047**(RIVTEMP-20.0);
LA20 = BOD_UP * (FLOW/Q_UP);
LA = LA20 * (0.02 * RIVTEMP + 0.60);
DOSATR = 14.65 - 0.41*RIVTEMP + 0.008*RIVTEMP**2 - 0.00008*RIVTEMP**3;
DEF=DOSATR-DO_UP;
IF FORM(T) = 'RES' THEN DO;
W = FLOW * (86400.0/VOLUME);
Z = Q_UP * (86400.0/VOLUME);
A = K1 + K3 + W;
B = K2 + W;
BOD_IN:  L_DWN = LA_INIT*(1.0/(2.71**(A*TIME))) + ((Z*LA)/A) *
   (1.0-1.0/(2.71**(A*TIME)));
C = DEF_INIT - (Z*DEF)/B;
D = K1 / (A-B);
E = LA_INIT - (Z*LA)/B;
F = 1.0/(2.71**(B*TIME));
G = K1/(B-A);
H = LA_INIT - (Z*LA)/A;
I = 1.0/(2.71**(A*TIME));
J = Z/B;
K = DEF + (K1*LA)/A;
DEF_IN:  DEF_DWN = (C+(D*E))*F + (G*H)*I + (J*K);
END;
ELSE DO;
L_DWN = (LA - X/K1) * (1.0/(2.71**(K1*TIME))) + X/K1;
EXP1 = 1.0 / (2.71**(K1*TIME));
EXP2 = 1.0 / (2.71**(K2*TIME));
IF K2 = K1 THEN DO;
L = K1 * TIME;
O = (LA-X)/K1;
P = (X+Y)/K1;
DEF_DWN = (L*O + DEF + P) * EXP1 - P;    END;
ELSE DO;
DEF_DWN = ((K1*LA - X) / (K2-K1)) * (EXP1 - EXP2) + ((X+Y)/K2) *
   (1.0-1.0/(2.71**(K2*TIME))) + DEF*(1.0/(2.71**(K2*TIME)));    END;
END;
IF LENGTH < (0.1*5280.0) THEN DO_DWN = DO_UP;
ELSE DO_DWN = DOSATR - DEF_DWN;
PRINT_IN:PUT SKIP EDIT(REACH,TYPE,UPSTM,DWNSTM,FLOW,CSA,TIME,K1,K2,
   DO_UP,DO_DWN)(COL(2),A(3),COL(9),A(3),COL(17),F(6,2),COL(28),F(6,2),
   COL(37),F(6,1),COL(50),F(6),COL(68),F(5,2),COL(79),F(5,3),COL(90),
   F(5,3),COL(101),F(4,1),COL(113),F(4,1));
Q_UP=FLOW;
BOD_UP = L_DWN / (0.02 * RIVTEMP + 0.6);
DEF_UP = DOSATR - DO_DWN;
K120_UP=K120_MIX;
GO TO ADD;
END;
/***************************************************************************/
```

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```
/**************************************************************/
/***************** INDUSTRY WITHDRAWING WATER FROM RIVER **************/
/** REACH IN WHICH AN INDUSTRY'S WITHDRAWAL AND DISCHARGE POINTS ****/
/********** ARE CLOSE ENOUGH TO BE CONSIDERED AS ONE POINT ***********/
/**************************************************************/
/**************************************************************/
ELSE IF TYPE='INC' THEN DO;
IND_WTHDRW_CON: GET EDIT(UPSTM,DWNSTM,WTHDR,ZILCH)(COL(25),F(6,2),
   COL(35),F(6,2),COL(45),F(6,2),X(29),A(1));
IF N=1 THEN DO_UP=DO;
ELSE DO_UP=DOSATR-DEF_UP;
FLOW=Q_UP+(WTHDR*1.545);
DO_DWN=DO_UP;
LA20 = BOD_UP * (FLOW/Q_UP);
PRINT_INC: PUT SKIP EDIT(REACH,TYPE,UPSTM,DWNSTM,FLOW,DO_UP,DO_DWN)
   (COL(2),A(3),COL(9),A(3),COL(17),F(6,2),COL(28),F(6,2),COL(37),
   F(6,1),COL(101),F(4,1),COL(113),F(4,1));
Q_UP=FLOW;
BOD_UP = LA20;
DEF_UP=DEF_DWN;
K120_UP=K120_MIX;
GO TO ADD;
LAST:END START;
```

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APPENDIX II

DATA FOR EACH REACH

FOR

JUNE 1972--SEPTEMBER 1972

TABLE XI

CLASSIFICATION, RIVER MILE LOCATION, AND CHANNEL DIMENSIONS OF WARRIOR RIVER REACHES

Reach No.	Classi-fication	Upstream River Mile	Downstream River Mile	Average Width (ft.)	Average Depth (ft.)
1A	SD	385.00	382.00	1125	54.7
2A	SD	382.00	367.50	1270	71.7
3A	SDH	367.50	366.00	1250	83.7
4A	R	366.00	365.00	1440	85.7
5A	N	365.40	361.50	1140	32.5
6A	SDH	361.50	347.50	1240	60.5
7A	R	347.50	346.90	1500	76.5
8A	N	346.90	346.30	970	16.9
9A	SD	346.30	345.70	500	22.9
10A	IWC	345.70	345.70	---	- -
10B	ID	345.70	345.20	520	19.9
10C	SDH	345.20	344.40	520	19.9
11A	IWC	344.40	344.40	---	- -
11B	ID	344.40	344.39	470	20.4
11C	ID	344.39	343.70	470	20.4
12A	SDH	343.70	343.50	500	19.9
13A	ID	343.50	343.00	530	19.4
14A	IW	343.00	342.50	640	18.9
15A	ID	342.50	341.60	500	19.9
16A	SDH	341.60	338.41	590	34.9
17A	ID	338.41	338.39	470	49.9
18A	R	338.39	338.10	750	51.4
19A	N	338.10	337.00	510	25.0
20A	IW	337.00	336.70	410	25.3
21A	ID	336.70	335.00	350	25.5

TABLE XII

INPUT DATA FOR WARRIOR RIVER REACHES

Reach No.	Month	Input Flow (cfs)	River Temperature (°C)	BOD_5 Input (ppm)	D. O. Input (ppm)	k_1 20 °C Input (base 10) (days^{-1})	Temperature Input (°C)	BOD_5 of River (ppm)	D. O. of River (ppm)	k_2 20 °C of River (base 10) (days^{-1})
1A	June	1895.0	27.0	2.5	6.0	0.060	27.0			
	July	2150.0	27.9	3.2	6.7	0.060	27.9			
	August	1615.0	30.0	1.0	6.6	0.060	30.0			
	September	1975.0	28.0	3.0	5.9	0.060	28.0			
2A	June	65.0	27.7	2.5	7.0	0.060	25.6			
	July	100.0	29.0	3.5	5.2	0.060	28.9			
	August	100.0	30.0	3.5	7.1	0.060	28.9			
	September	125.0	28.5	2.5	6.5	0.060	25.0			
3A	June	10.0	28.5		8.0		20.0			
	July	10.0	28.0		8.0		22.2			
	August	15.0	29.1		8.0		22.8			
	September	10.0	28.9		8.0		22.8			
4A	June	1970.0	28.5					1.0	3.7	0.060
	July	2260.0	27.5					1.5	3.4	0.050
	August	1730.0	29.1					1.5	5.1	0.060
	September	2110.0	28.9					1.5	3.0	0.060

TABLE XII (Continued)

Reach No.	Month	Input Flow (cfs)	River Temperature (°C)	BOD_5 Input (ppm)	D. O. Input (ppm)	k_1 20 °C Input (base 10) ($days^{-1}$)	Temperature Input (°C)	BOD_5 of River (ppm)	D. O. of River (ppm)	k_1 20 °C of River (base 10) ($days^{-1}$)
5A	June	0.0	27.3							0.055
	July	0.0	26.2							0.055
	August	0.0	28.2							0.055
	September	0.0	27.8							0.055
6A	June	15.0	26.7		5.0		22.2			
	July	25.0	26.0		5.0		23.3			
	August	10.0	29.0		4.6		26.7			
	September	15.0	28.3		4.8		26.7			
7A	June	1880.0	28.3					2.7	4.6	0.095
	July	2270.0	27.5					3.5	4.3	0.095
	August	1730.0	28.9					4.0	3.9	0.095
	September	2040.0	28.0					4.0	4.4	0.095
8A	June	0.0	25.7							0.065
	July	0.0	26.7							0.065
	August	0.0	27.2							0.065
	September	0.0	27.2							0.065
9A	June	25.0	25.7	2.0	8.0	0.060	25.6			
	July	35.0	26.7	2.5	8.0	0.060	28.9			
	August	25.0	27.2	2.5	8.0	0.060	28.9			
	September	15.0	27.2	2.6	9.4	0.060	25.6			

TABLE XII (Continued)

Reach No.	Month	Input Flow (cfs)	River Tempera- ture (°C)	BOD_5 Input (ppm)	D. O. Input (ppm)	k_1 20 °C Input (base 10) ($days^{-1}$)	Tempera- ture Input (°C)	BOD_5 of River (ppm)	D. O. of River (ppm)	k_1 20 °C of River (base 10) ($days^{-1}$)
10A	June	- 0.43								
	July	- 0.43								
	August	- 0.43								
	September	- 0.43								
10B	June	0.40	26.5	610.0	0.0	0.005	33.0			
	July	0.43	27.3	450.0	0.0	0.005	33.0			
	August	0.43	27.8	280.0	0.0	0.005	33.0			
	September	0.42	27.2	410.0	0.0	0.005	33.0			
10C	June	0.20	26.5	1550.0	0.0	0.025	33.0			
	July	0.20	27.3	1550.0	0.0	0.025	33.0			
	August	0.20	27.8	1550.0	0.0	0.025	33.0			
	September	0.20	27.2	1550.0	0.0	0.025	33.0			
11A	June	- 1.12								
	July	- 1.12								
	August	- 1.12								
	September	- 1.12								
11B	June	0.21	26.5	5.0	3.0	0.025	34.4			
	July	0.21	27.3	5.0	3.0	0.025	34.4			
	August	0.21	27.8	5.0	3.0	0.025	34.4			
	September	0.21	27.2	5.0	3.0	0.025	34.4			

TABLE XII (Continued)

Reach No.	Month	Input Flow (cfs)	River Temperature (^oC)	BOD_5 Input (ppm)	D. O. Input (ppm)	k_1 20 ^oC Input (base 10) ($days^{-1}$)	Temperature Input (^oC)	BOD_5 of River (ppm)	D. O. of River (ppm)	k_1 20 ^oC of River (base 10) ($days^{-1}$)
11C	June	0.70	26.5	84.0	0.0	0.085	33.0			
	July	0.80	27.3	52.0	0.0	0.085	33.0			
	August	0.78	27.8	54.0	0.0	0.085	34.0			
	September	0.72	27.2	46.0	0.4	0.085	33.0			
12A	June	70.0	26.5		7.5		25.0			
	July	110.0	28.0		7.0		28.9			
	August	110.0	27.8		7.0		27.8			
	September	140.0	27.2		7.5		24.4			
13A	June	3.50	26.5	2.2	5.0	0.002	24.0			
	July	3.50	28.0	2.2	5.0	0.002	24.0			
	August	3.50	27.8	2.2	5.0	0.002	24.0			
	September	3.50	27.2	2.2	5.0	0.002	24.0			
14A	June	- 18.00	26.5							
	July	- 18.00	28.0							
	August	- 18.00	27.8							
	September	- 18.00	27.2							
15A	June	12.00	27.0	100.0	0.0	0.135	35.0			
	July	12.00	27.5	100.0	0.0	0.135	35.0			
	August	12.00	27.8	100.0	0.0	0.135	35.0			
	September	12.00	27.2	100.0	0.0	0.135	35.0			

TABLE XII (Continued)

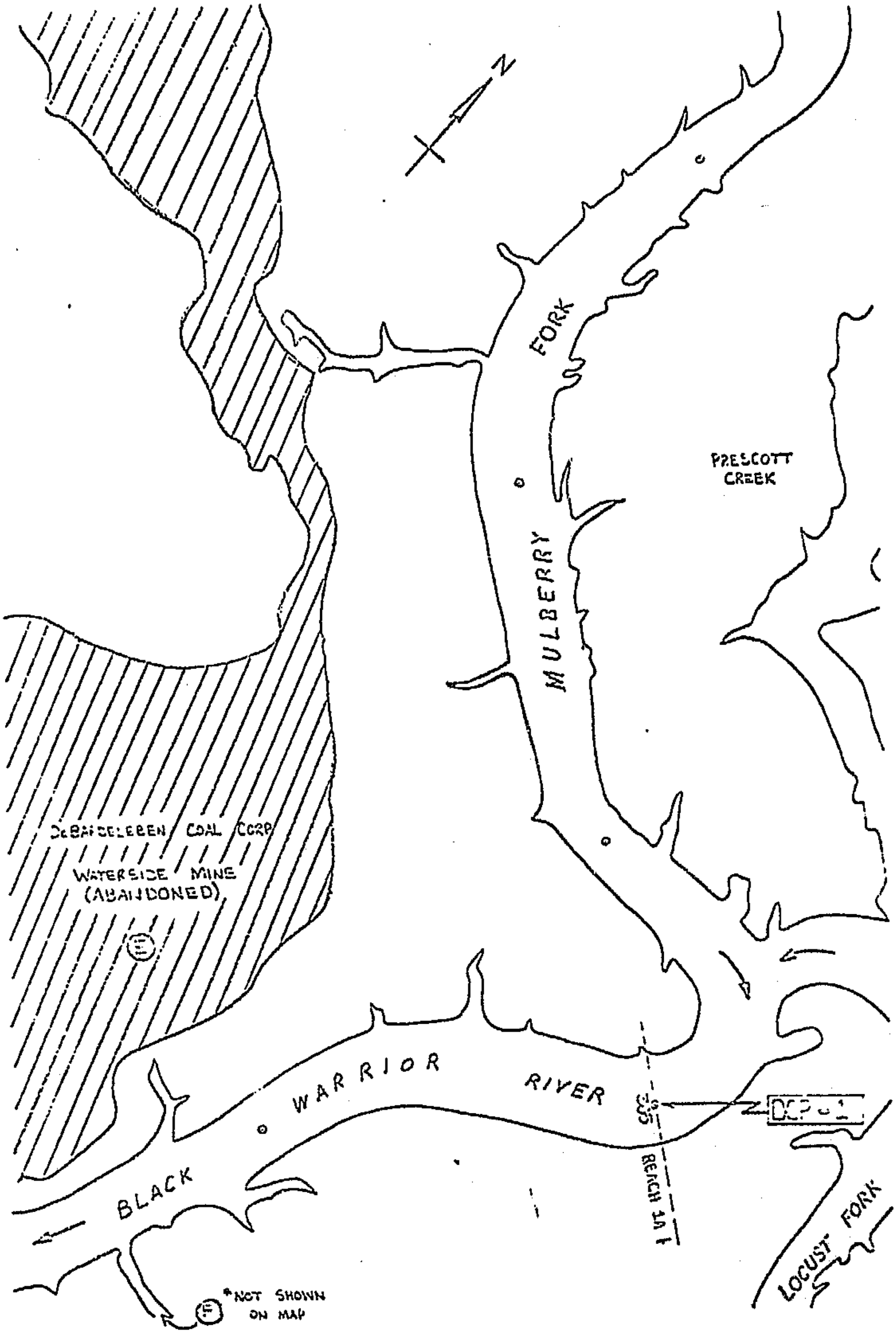
Reach No.	Month	Input Flow (cfs)	River Temperature (°C)	BOD_5 Input (ppm)	D. O. Input (ppm)	k_1 20 °C Input (base 10) ($days^{-1}$)	Temperature Input (°C)	[illegible]	D. O. of River (ppm)	k_1 20 °C of River (base 10) ($days^{-1}$)
16A	June	0.6	27.0		4.0		21.0			
	July	0.4	27.5		4.0		23.0			
	August	0.5	27.8		4.0		22.0			
	September	0.6	27.2		4.0		21.0			
17A	June	0.32	26.7	58.0	7.0	0.100	27.0			
	July	0.50	28.5	40.0	8.0	0.100	28.0			
	August	0.38	27.8	28.0	9.0	0.100	28.0			
	September	0.50	27.2	60.0	7.0	0.100	27.0			
18A	June	2150.0	26.7					[illegible]	6.6	0.040
	July	2630.0	28.5					[illegible]	5.7	0.040
	August	2000.0	27.8					[illegible]	5.4	0.040
	September	2320.0	27.2					[illegible]	6.7	0.040
19A	June	0.0	26.7							0.020
	July	0.0	28.5							0.020
	August	0.0	27.8							0.020
	September	0.0	27.8							0.020
20A	June	- 0.40	26.7							
	July	- 0.40	28.5							
	August	- 0.40	27.8							
	September	- 0.40	27.8							

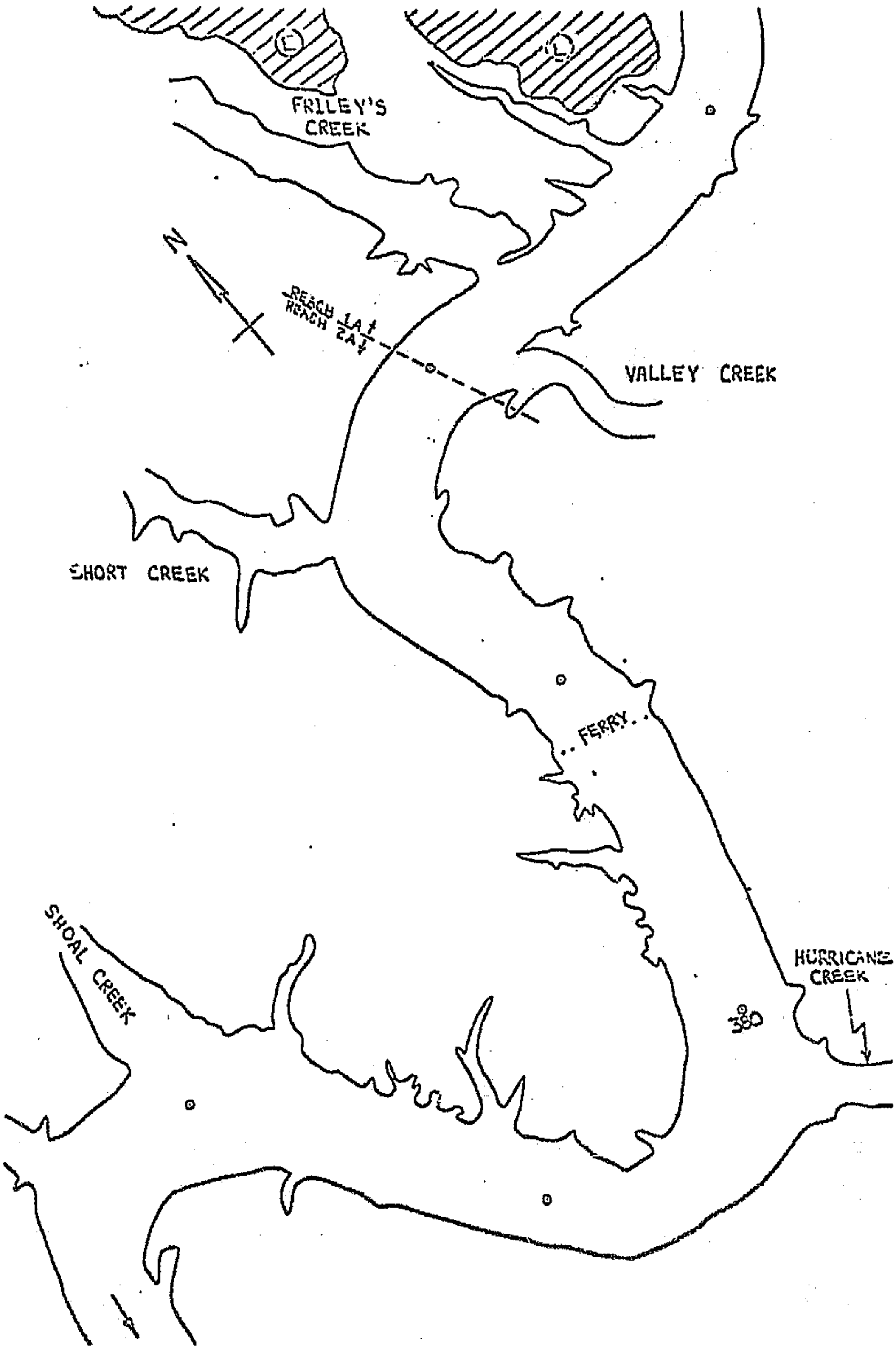
TABLE XLI (Continued)

Reach No.	Month	Input Flow (cfs)	River Temperature (^oC)	BOD_5 Input (ppm)	D. O. Input (ppm)	k_1 20 ^oC Input (base 10) ($days^{-1}$)	Temperature Input (^oC)	BOD_5 of River (ppm)	D. O. of River (ppm)	k_1 20 ^oC of River (base 10) ($days^{-1}$)
21A	June	0.46	26.7	22.0	2.9	0.025	35.0			
	July	0.46	28.5	22.0	2.9	0.025	35.0			
	August	0.46	27.8	27.0	3.0	0.025	35.0			
	September	0.46	27.8	27.0	3.0	0.025	35.0			

APPENDIX III

DETAILED MAPS OF THE SECTION OF THE WARRIOR RIVER USED IN THE MODELING STUDY


N
FORK
MULBERRY
PRESCOTT CREEK
COAL CORP
WATERSIDE MINE
(ABANDONED)
BLACK WARRIOR RIVER
REACH 1A
LOCUST FORK
*NOT SHOWN ON MAP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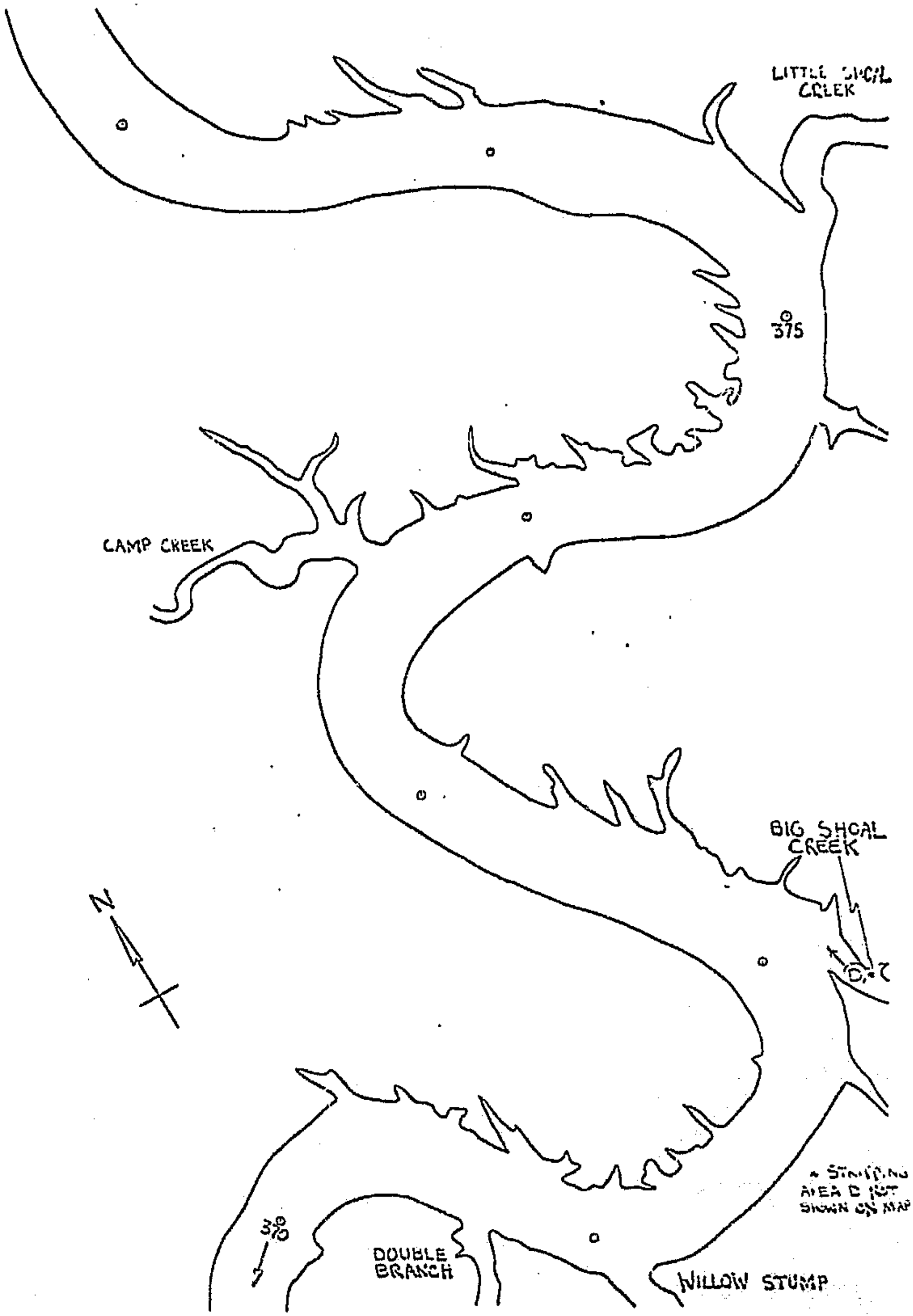
REACH 2A ↓
VALLEY CREEK
SHORT CREEK
FERRY
SHOAL CREEK
HURRICANE CREEK
380



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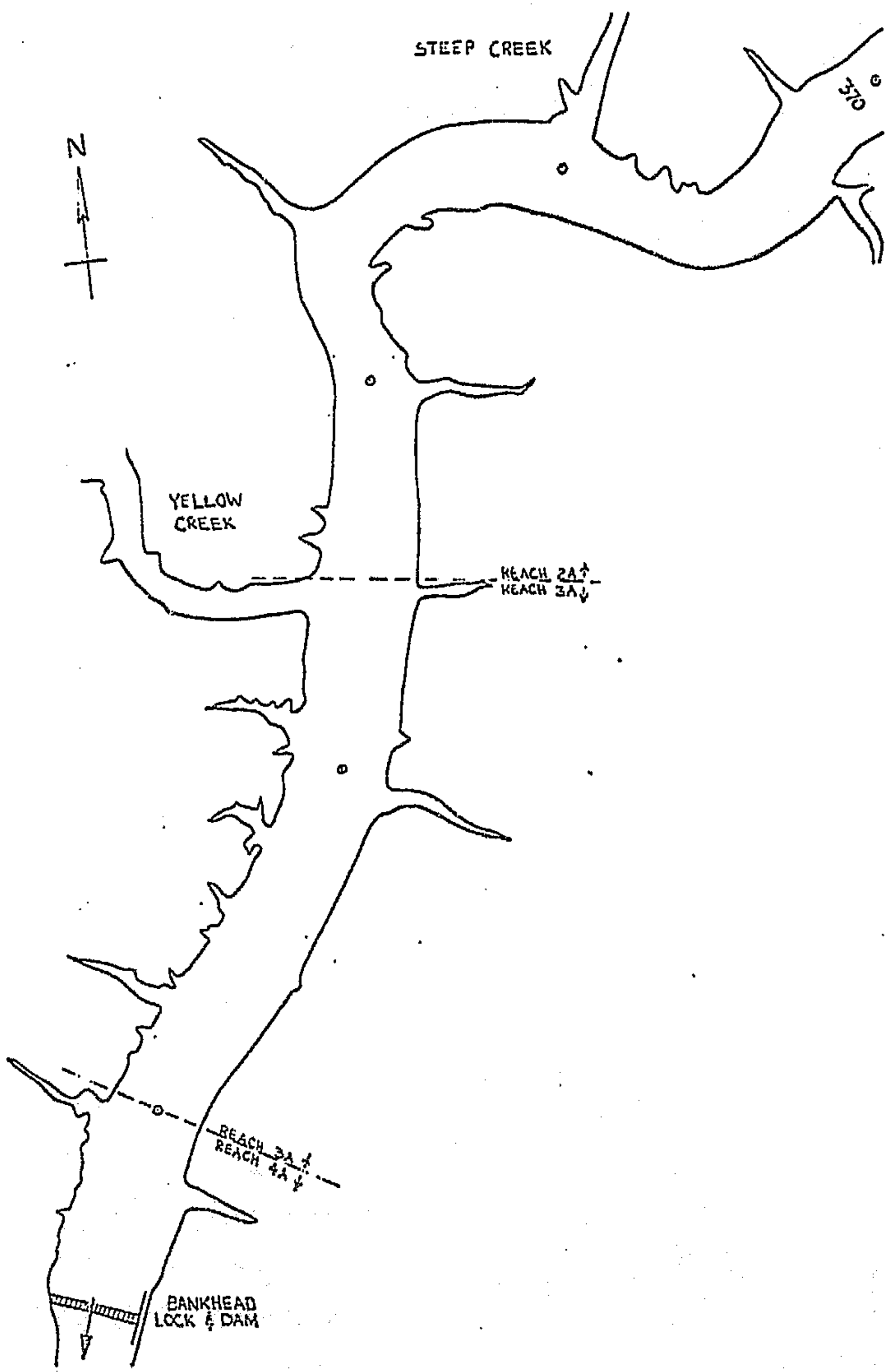
370
DOUBLE
BRANCH
WILLOW STUMP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REACH 3A
REACH 4A
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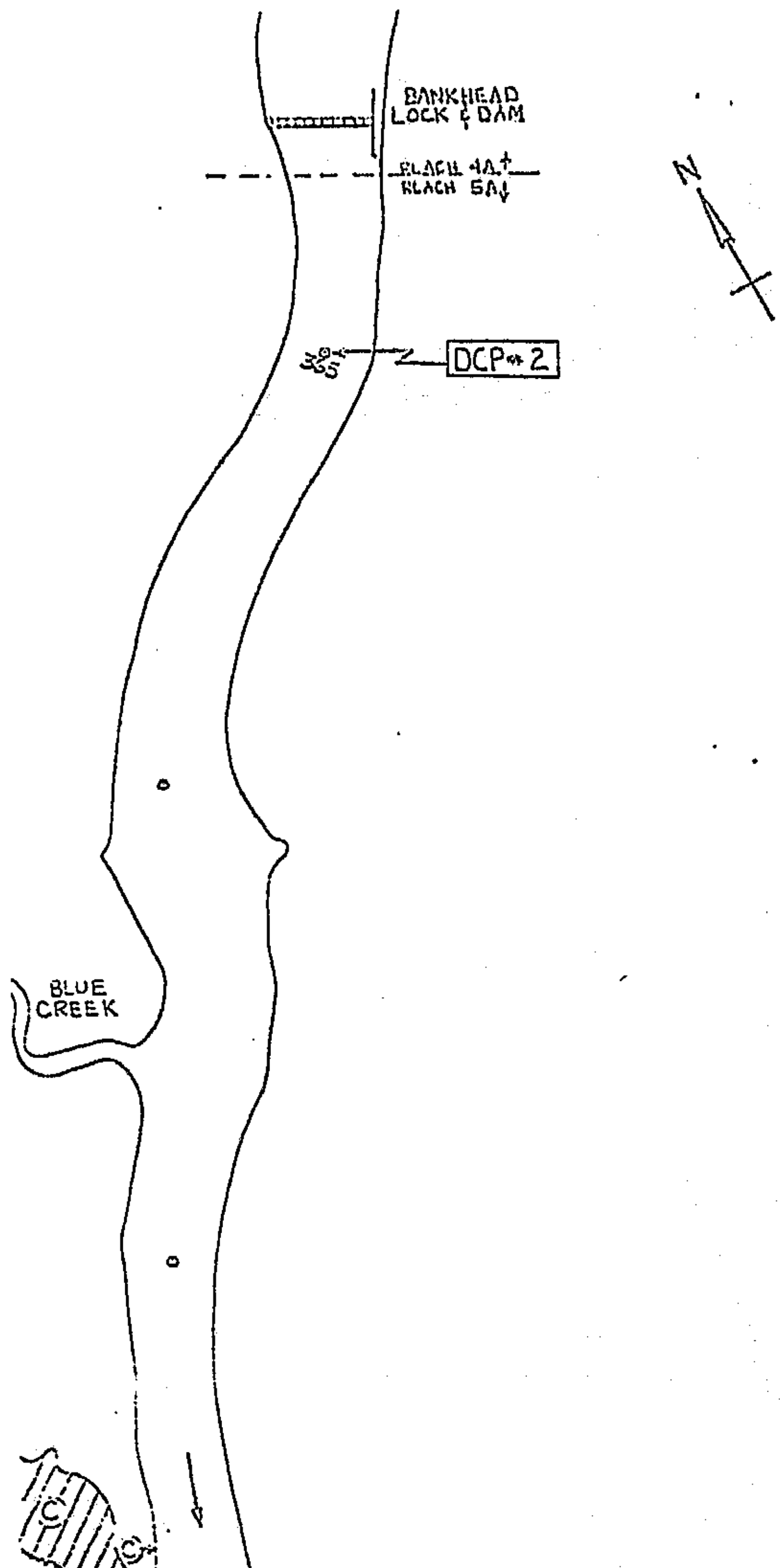
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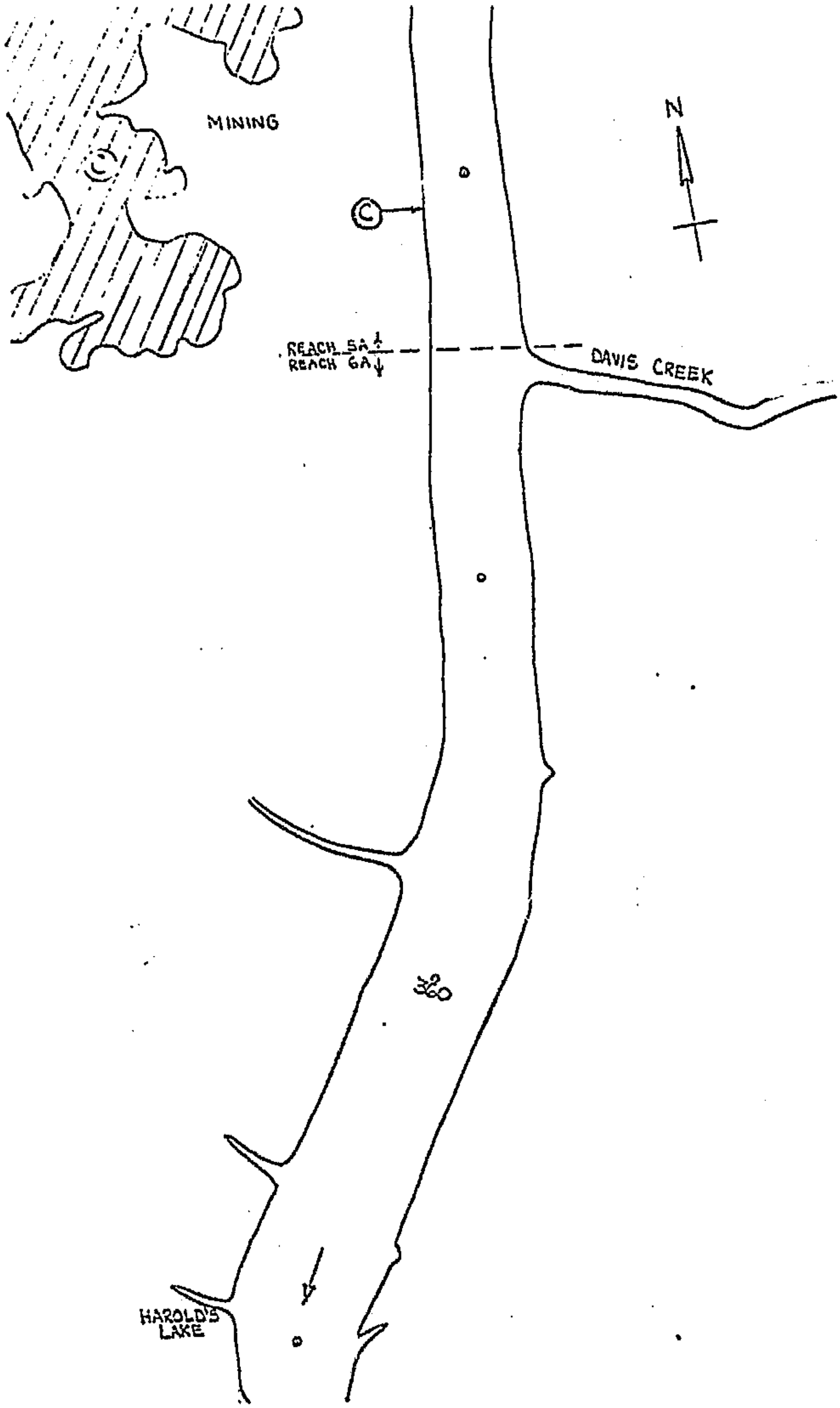

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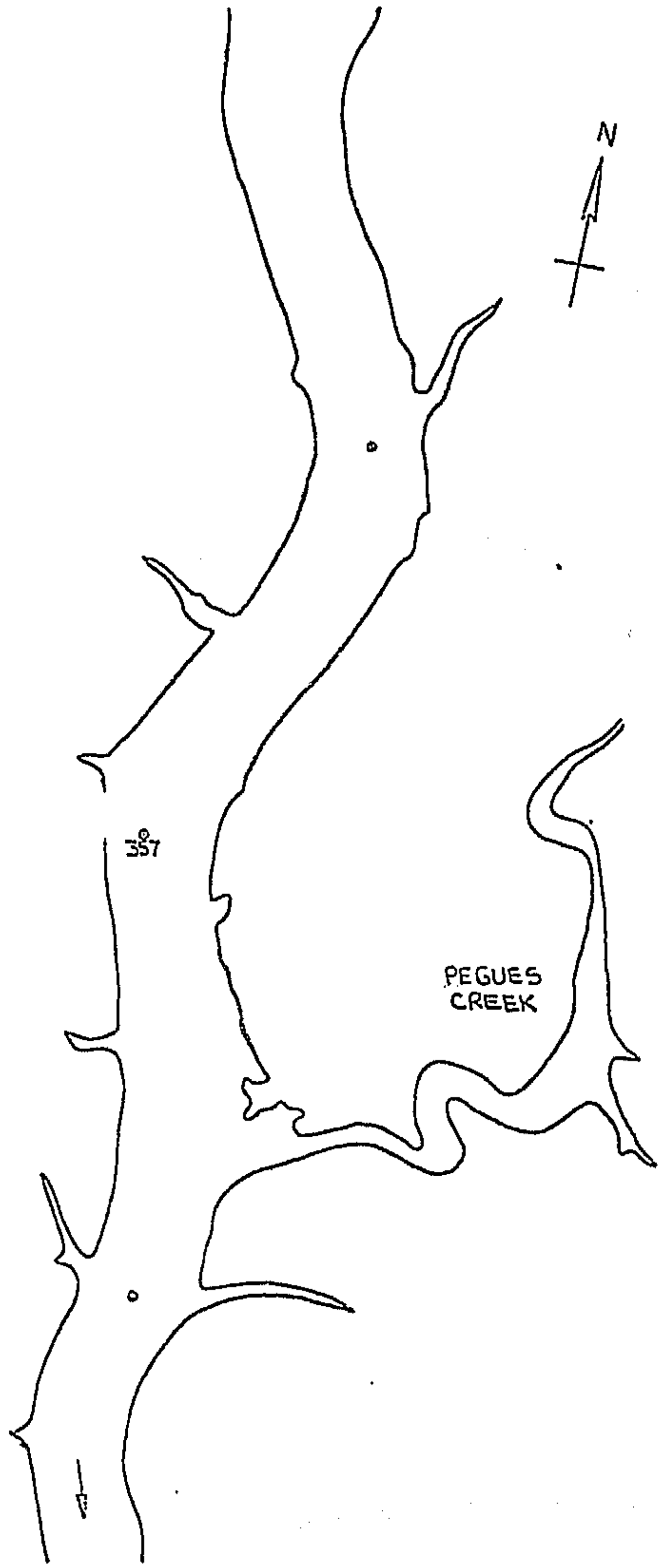
REACH 5A
REACH 6A
DAVIS CREEK
HAROLD'S
LAKE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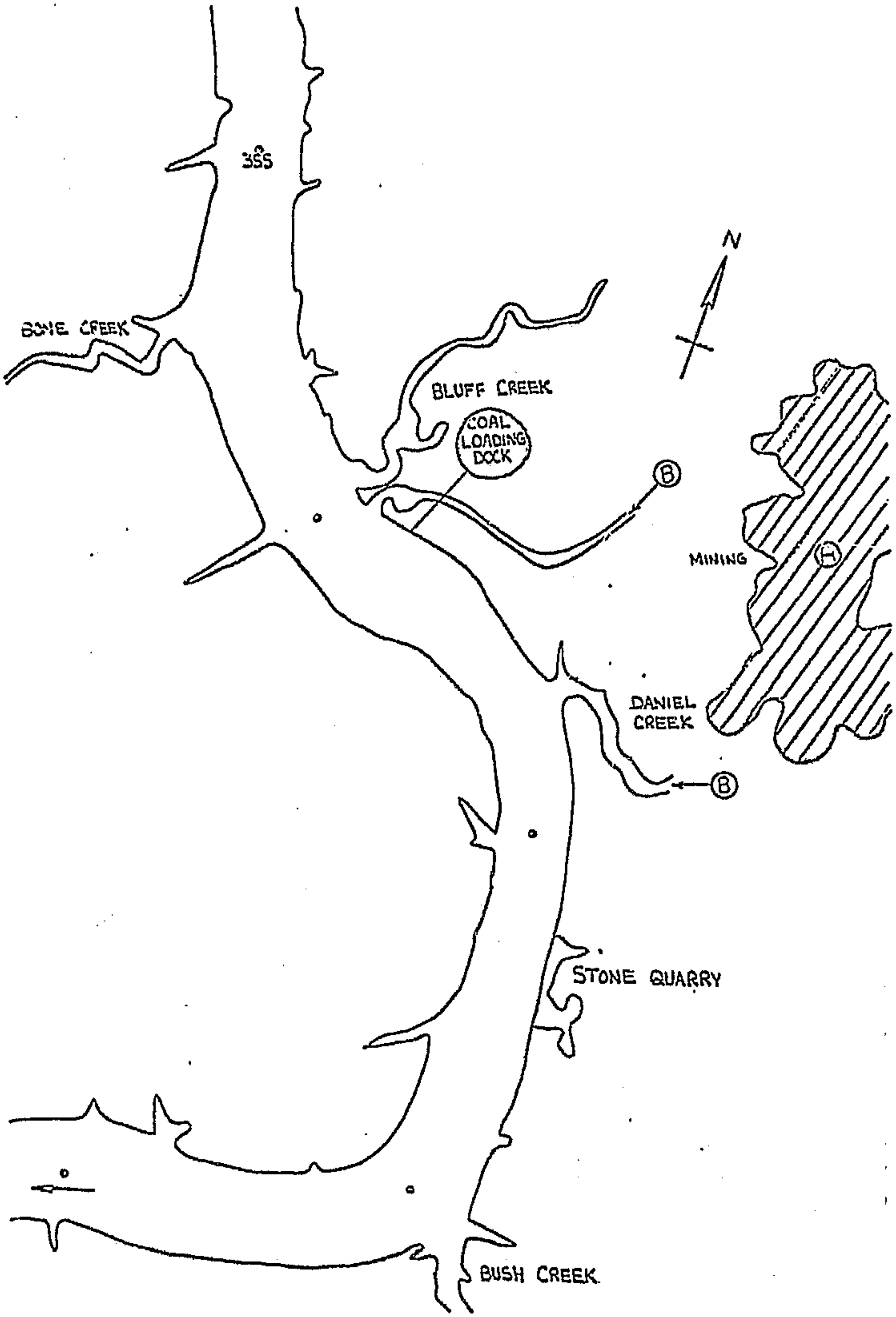
355
BONE CREEK
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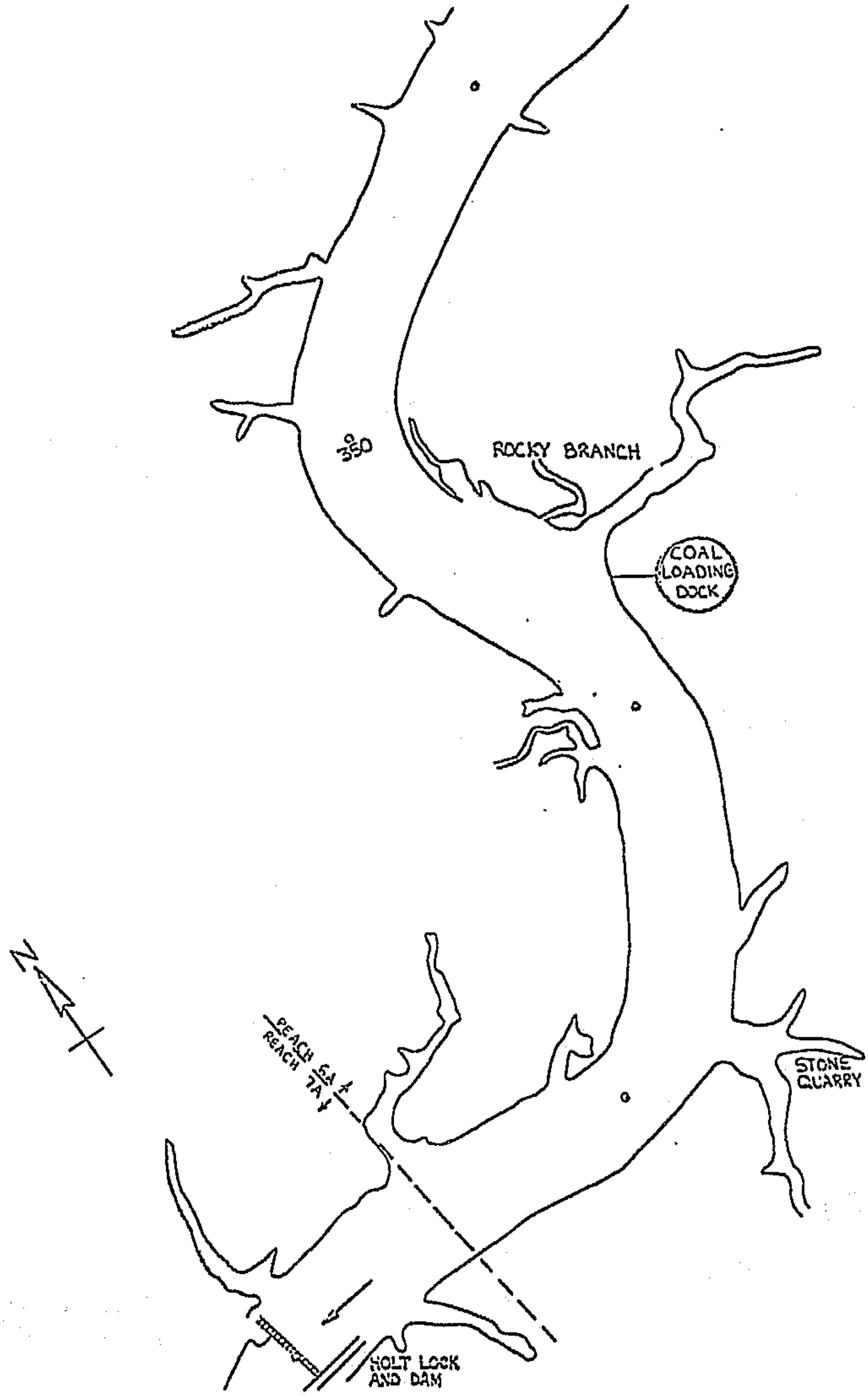
BLUFF CREEK
COAL LOADING DOCK
B
MINING
H
DANIEL CREEK
B
STONE QUARRY
BUSH CREEK



350
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COAL LOADING DOCK
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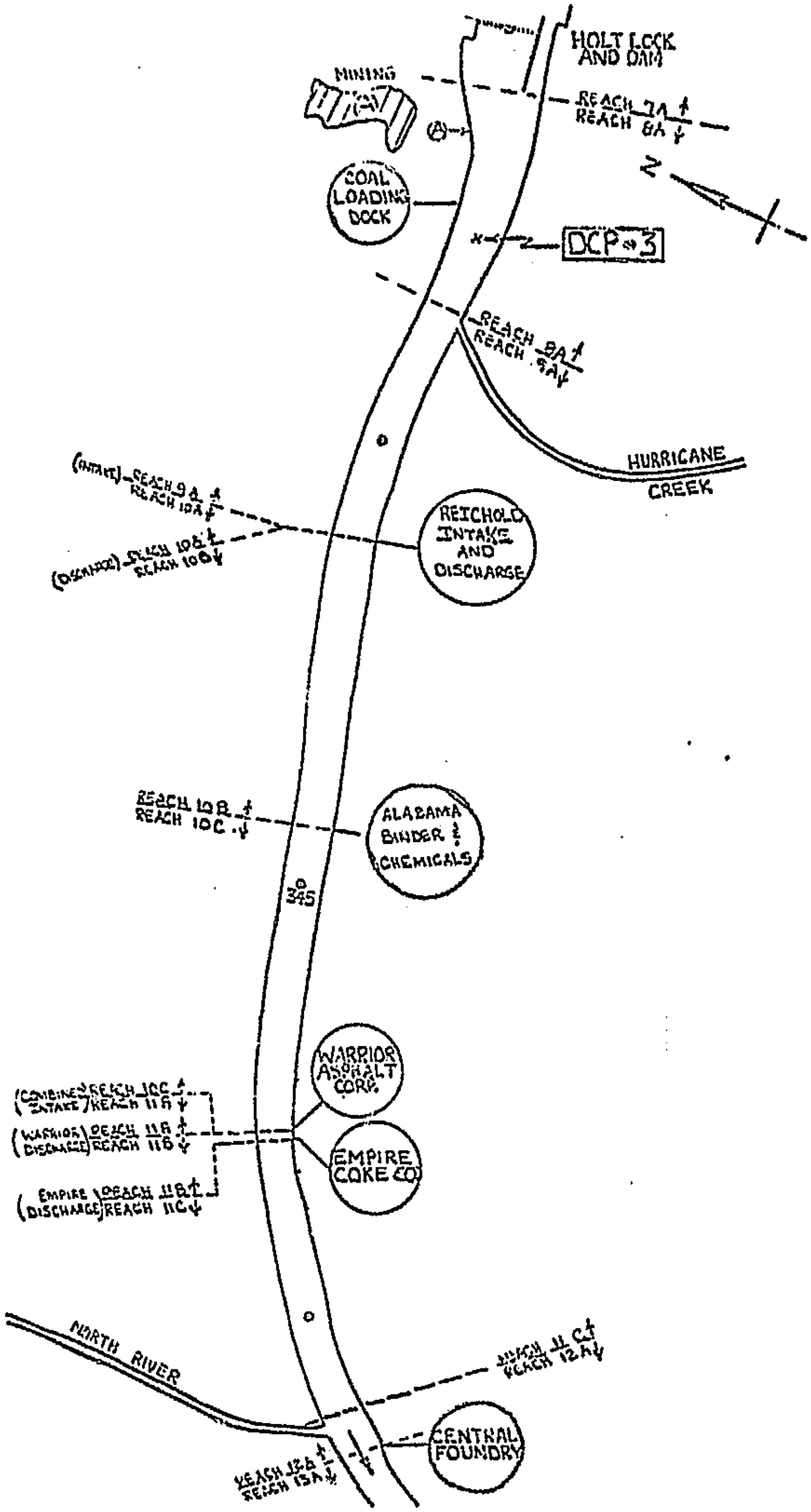
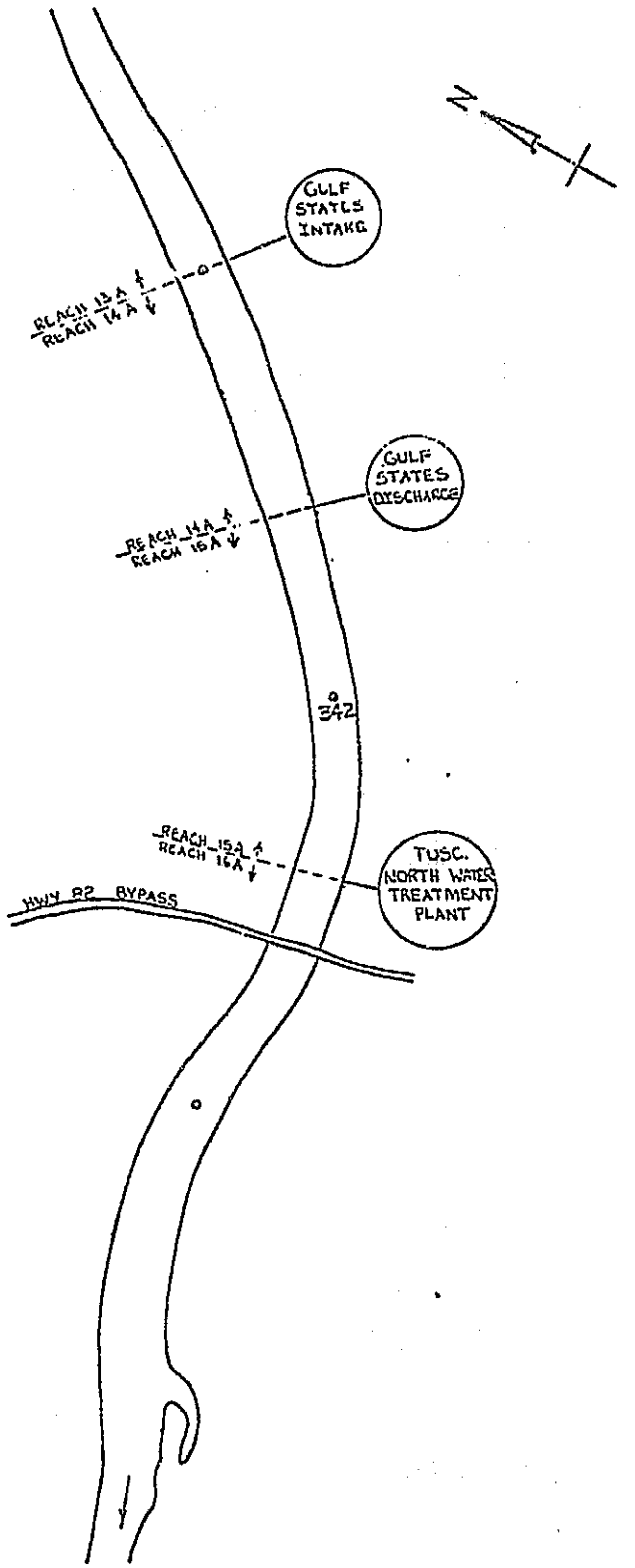
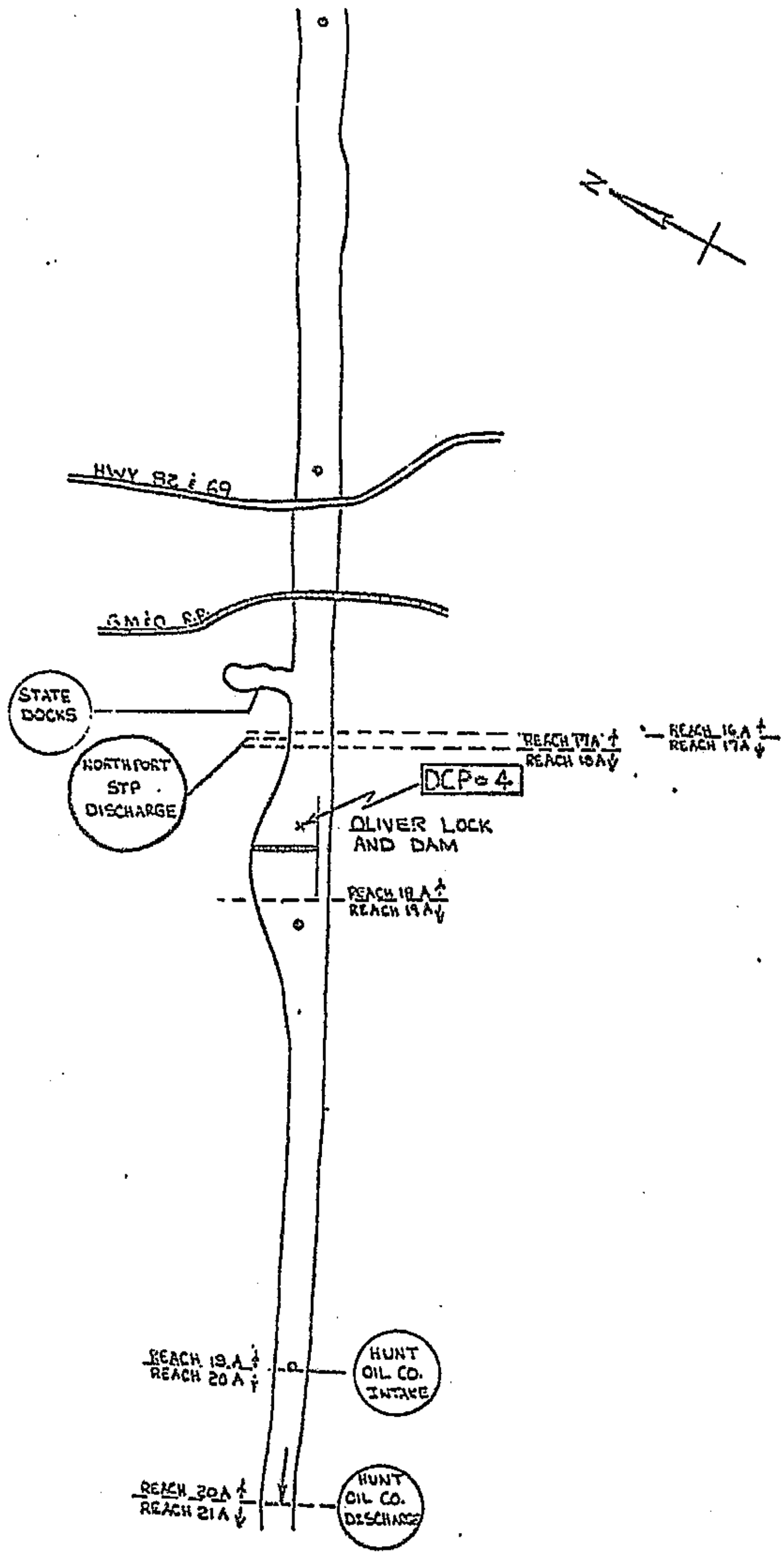
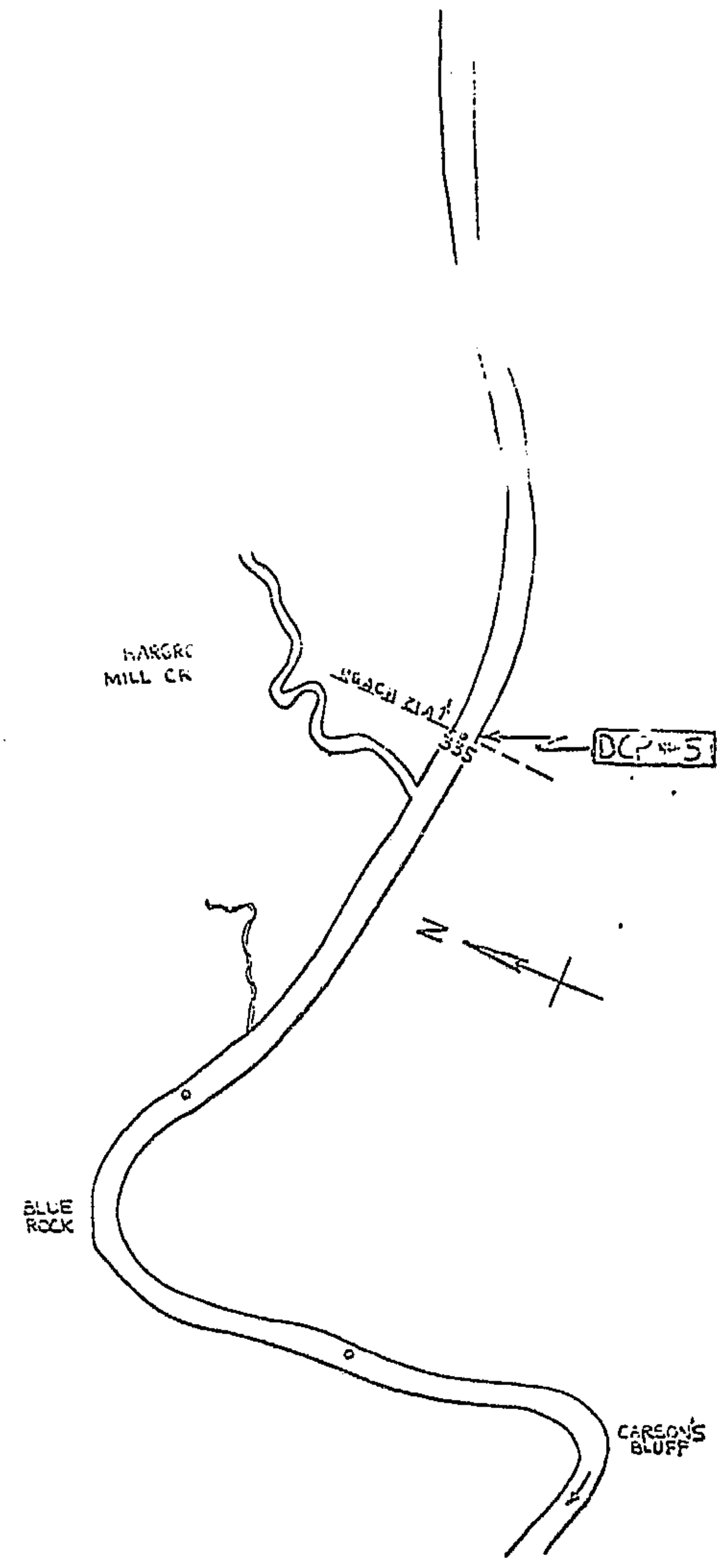
REACH 6A
REACH 7A
STONE QUARRY
HOLT LOCK AND DAM


HOLT LOCK AND DAM
MINING
COAL LOADING DOCK
DCP #3
HURRICANE CREEK
REITCHOLD INTAKE AND DISCHARGE
ALABAMA BINDER & CHEMICALS
345
WARRIOR ASPHALT CORP.
EMPIRE COKE CO.
NORTH RIVER
CENTRAL FOUNDRY


N
GULF STATES INTAKE
REACH 13A
REACH 14A
GULF STATES DISCHARGE
REACH 14A
REACH 15A
342
REACH 15A
REACH 16A
TUSC. NORTH WATER TREATMENT PLANT
HWY 82 BYPASS



HWY 82 & 69
GM&O R.R.
STATE DOCKS
NORTHPORT STP DISCHARGE
REACH 17A ↑
REACH 18A ↓
REACH 16A ↑
REACH 17A ↓
DCP-4
OLIVER LOCK AND DAM
REACH 18A ↑
REACH 19A ↓
REACH 19A ↑
REACH 20A ↓
HUNT OIL CO. INTAKE
REACH 20A ↑
REACH 21A ↓
HUNT OIL CO. DISCHARGE



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PROJECTING THE POTENTIAL DIFFUSION OF THE GYPSY MOTH (PORTHETRIA DISPAR) AND DELINEATING SOME SUSCEPTIBLE AREAS IN ALABAMA USING REMOTELY SENSED IMAGERY

Glenn R. Pritchett

SECTION EIGHT

of

VOLUME TWO

INVESTIGATIONS USING DATA IN

ALABAMA FROM ERTS-A

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PROJECTING THE POTENTIAL GEOGRAPHIC DIFFUSION OF THE GYPSY MOTH (PORTHETRIA DISPAR) AND DELINEATING SOME SUSCEPTIBLE AREAS IN ALABAMA USING REMOTELY SENSED IMAGERY

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CHAPTER I

INTRODUCTION

The gypsy moth (Porthetria dispar) is a forest insect native to eastern Europe and Asia where it causes moderate and infrequent damage. However, when taken from its native environment, the insect displays a capacity for changing into a costly and destructive menace to forests. In 1869 such a transition was begun when a French biologist introduced gypsy moth eggs into Medford, Massachusetts. He hoped to produce a sturdy strain of silk-producing insects by crossing the gypsy moth with the silkworm moth and raising it in a very conducive environment. As could be expected, these larvae escaped from the Medford experiment, thus creating the current gypsy moth infestation problem in the northeastern United States.[1]

During these subsequent years of habitation in this favorable environment, the gypsy moth has spread over 200 thousand square miles while defoliating forest and ornamental trees in the process. The moth has now become established in all or portions of nine states from Maine to Maryland. Past records of outbreaks within this area have shown preferred hosts to consist mainly of hardwoods but with older larvae successfully feeding on pine, cedar or spruce. These conifers are usually killed by one season of complete defoliation while hardwood species may be killed by two successive years of defoliation. In areas having 50 percent or more hardwood trees (preferred hosts) there is generally a three to five year phase following initial introduction

in which the insect becomes generally distributed at low densities throughout the region. Phase two may bring a population explosion throughout the entire area for several years in succession. Eventually, a population collapse occurs followed by local abundance on the more susceptible upland oak sites.[2]

The potential threat of the gypsy moth to southern forest resources has been analyzed by several persons over the past forty years, and their findings reveal some interesting speculations. On the basis of suitable hosts being present, the insect is expected to eventually occupy the entire region in which oaks are a component of the forest stands. Evidence is accumulating to indicate that southern hardwood forests might be highly susceptible to defoliation, and therefore, may experience greater mortality than that occurring in the Northeast.[3] This factor, combined with a milder climate and a virtual predator-free habitat in the Southeast, offers some very bleak possibilities.

Purpose

It appears that in the past very little attention has been given the possibility of utilizing remotely sensed data, and more specifically ERTS-I (Earth Resources Technology Satellite) imagery as an effective tool in the investigation of significant, large scale insect infestations of our forests. Accepting the existence of such a problem, the need for a relatively quick, inexpensive and accurate means of surveying a current habitat, as well as the destructive end result of these pests' presence is of prime concern.

Armed with evidence gathered by conventional research techniques, authorities feel that an indicated spread of one of our most deletorious forest insects, the gypsy moth, is and will continue to be in a southerly direction, thus posing a direct threat to southern forests. Therefore, the contention here is that such a potential destructive capability of the continued migration should warrant a more in-depth examination of such a possibility. The proposition that remote sensing techniques can be effectively implemented in predicting a trend of the gypsy moth population movement into Alabama is the primary theme of this work.

Scope and Procedure

Because such a topic for evaluation as the gypsy moth with its propulsive character could easily become an open-ended study, it will be necessary to limit the extent of this investigation to the basic factors of population dynamics. The primary format to be followed will be the review of the adaptive traits and destructive nature of the insect, the application of such characteristics of the pest to possible future effects on the environment, and the analysis of such inherent qualities, as well as other extraneous factors in their relevancy to potential population growth and movements.

Furthermore, it is necessary to restrict the scope of this study to include such objectives as: 1) the enumeration and summary of such behavioral patterns as life cycle, rate of reproduction, preferred habitats and modes of population spread which are essential to the better understanding of population changes, 2) an analysis of and subsequent prediction of population diffusion (both direction and rate) which

necessitate a review of historical population censuses, a determination of the effects of past and present eradication efforts on population growth and a delineation of a natural corridor for mass movement from the present infestation area into Alabama, and 3) the summary of the potential gypsy moth threat to Alabama and the mapping of representative target areas using remotely sensed data.

The initial phase of historical data procurement for the purpose of preparing a background sketch of the gypsy moth was accomplished via library research and inspection of Animal and Plant Health Inspection Service (United States Department of Agriculture) records of past population surveys. These data were also useful in the forecasting of population trends, along with such procedures as: 1) determining the net effect of natural restrictions on the potential population spread, 2) analyzing the net effect of artificial suppression measures on population growth and subsequent dispersion, 3) utilizing non-linear regression techniques to predict progressive population diffusion (by total area expansion and direction of predominant spread), and 4) using ERTS-I imagery to illustrate an unbroken chain of favorable environs and preferred host forests along the Valley and Ridge Province of the Appalachian Mountains from Pennsylvania to north Alabama.

With the credibility of such an approximate prognostication accepted, the desirability of defining specific infestation target areas in Alabama is thus enhanced. This goal may be achieved by employing color composite ERTS-I imagery in conjunction with ground truth data and color infra-red aircraft photography where available for verification of the location of certain forest stand types. In addition, color composite ERTS-I imagery of New England infestation areas is included for correlation with imagery

of Alabama for future reference in the monitoring of the approaching gypsy moth outbreaks. However, the use of these images as detection tools will probably prove fruitless since extensive investigation of them revealed no unique spectral signatures which could be directly attributable to gypsy moth defoliation. The reason for this limitation of ERTS data is caused by the undergrowth usually found in hardwoods which would be interpreted by the multi-spectral scanners as the same reflectance value (in the defoliated area) which would have been reflected by the forest canopy. These New England images are, therefore, included only for purposes of comparisons with surface features in Alabama.

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[2]*Ibid.*, p.6

[3]*Ibid.*, p. 8

CHAPTER II

ENUMERATION AND DESCRIPTION OF SIGNIFICANT BEHAVIORAL TRAITS

For a better understanding of the present success status of the gypsy moth, the many inherent characteristics which have enabled it to thrive in a somewhat new environment must be considered. This unusual adaptive capacity is perhaps best illustrated by a comprehension of the insect's native habitat, Europe and Asia. By encompassing such a vast expanse of territory with its tremendous variety of climatic regimes, topography and vegetation cover, the moth's ability to meet the demands of new and sometimes hostile surroundings can thus be demonstrated.

Description of Life Cycle

A closer look at those morphological attributes of the gypsy moth which contribute to such a high degree of success in geographic expansion reveal: 1) a great reproductive capacity (usually 300-500 eggs per female, 2) polyphagous[1] habits, and 3) morphological and behavioral adaptations.[2] Such traits are completely necessary when one considers the confinement of the insect to such a short life span of only one year. The life cycle includes the usual four stages: 1) egg, 2) larva (with five to six instars[3]), 3) pupa, and 4) adult. The most vulnerable of these stages seem to be the egg and larval phases because of assailability to enemies during these periods. But a possible compensating

trait is the high mobility of the adult male. Although adult females are flightless because of their large egg-laden abdomen, the male is a strong flier, being able to cross great distances, thus creating a stronger gene pool by inter-breeding with other populations.[4]

In the cooler climates such as in New England, only one generation per year occurs, with the harsh winters being spent in the egg stage which lasts from July or August to April. The destructive larvae hatch in April, approximating the arrival of new broad leaves, meaning that the insect can feed at a voracious rate until the July pupal stage. Adults, which do not feed at all, emerge in late July, mate and die, thus completing the life cycle.[5]

Factors of Reproduction

Aside from the tremendous egg-carrying capacity of the female, the very strong sex drive is, in itself, a very significant factor in the gypsy moth's ability to replenish its population. The lure of the female can attract males from as much as two miles away, thereby insuring the necessary cross breeding, though the geographic density of males and females may be quite low.[6]

This process of natural selection in conjunction with the feeding habits of the larvae, strangely enough, increases the probability of survival for the populace. When a population booms, resulting in a heavily infested stand of timber, the entire crop of foliage may be consumed before the larvae reach maturity. When this saturation occurs, two possible reactions result: 1) the larvae will vacate the trees and migrate considerable distances in search of food or 2) when the food supply is depleted but not completely consumed before the larvae reach maturity,

many succeed in pupating although they are smaller than normal size. The latter possibility results in smaller adults which reduces the number of eggs deposited per mass.[7] Since there remains a direct relationship between pupal weights of females and the numbers of eggs produced by females emerging from these pupae, the converse condition of a light infestation with faster developing larvae (because of an adequate food supply) can be expected to yield heavier females with a higher reproductive potential.[8] Therefore, a natural control of population size does exist, but seemingly on a localized basis only.

Preferred Habitat

Conditions conducive to gypsy moth outbreaks, as well as for most forest insects, are most likely to occur: 1) in pure timber stands rather than in stands of mixed composition, 2) in overmature rather than immature stands, and 3) in plantations rather than natural stands.[9] It can therefore be expected that the economic impact of each infestation will be quite severe, since each condition which must be met for insect survival correlates quite well with criteria for valuable tree species. For instance, the most valuable trees are building material-producing hardwoods as opposed to pulp-producing softwoods, are sufficiently homogeneous to provide for ease of accessibility, and are mature enough to bear fruit or to be of adequate size for extraction. In any event, of all members of the timber community, commercially-grown types (such as fruit orchards and pure pine stands) would seem to be the most vulnerable.

More specifically, preferred hosts are most dependent upon stage of larval development. The small first stage larvae must have tender, new leaves for survival preferably those found on young saplings, while the

older larvae are much more adaptable. First instar larvae depend on the availability of apple, beech, birch (gray, red and paper at high altitude), larch, linden, oaks (especially white and red), and white willows to develop. Older larvae are much less particular in their choice of food and will even attack hemlock, pines (red and white) and spruce when preferred hosts are not readily available.[10] For the complete list of gypsy moth food plants, see Table I.

Adaptation to Environment

Evolution has dealt kindly with the gypsy moth. Its ability to cope with the elements after being suddenly thrust into the new North American environment provided the sound basis for subsequent adaptive modifications.

The faster development time of the Canadian strains being quite evident indicates that specimens from colder climates have a more rapid rate of morphological development than those from warmer climates. If one can assume that the gypsy moth now present in North America originated from the single introduction from France, then this rather dramatic decrease in maturation time of specimens collected at the northern limits of the range in North America represents adaptation to a climate that has occurred in a comparatively short period of time, probably less than fifty generations.[11] The rate of development not only varies with temperature and humidity, but also with the considerable polymorphism within the various populations of this insect in North America.[12] However, since studies of variations within strains are lacking, factors of environmental determinism will have to take precedence in a determination of maturation agents differences in developmental rates.

TABLE 1

CLASSIFICATION OF FOOD PLANTS

Class I - Species that are favored food for the gypsy moth larvae.

Alder, Spreckled
Apple
Ash, Mountain
Aspen, American
Aspen, Large-toothed
Balm-of-Gilead
Beech, American
Birch, Gray
Birch, Paper
Birch, Red
Blueberry (V. angustifolium)
Box Elder
Gum, Red
Hawthorn
Hazelnut
Hazelnut, Beaked
Larch, American
Larch, European
Linden, American
Linden, European
Oak, Black
Oak, Rock Chestnut
Oak, Dwarf Chestnut
Oak, Bur.
Oak, Pin.
Oak, Post
Oak, Red
Oak, Scarlet
Oak, Bear
Oak, Shingle
Oak, Swamp White
Oak, White
Poplar, Lombardy
Rose, Pasture
Service-berry
Sumac, Mountain
Sumac, Scarlet
Sumac, Staghorn
Willow, White
Willow, Glaucous
Willow, Sandbar
Witch-hazel

Class II - Species that are favored food for gypsy moth larvae after the earlier larval stages.

Chestnut
Hemlock
Pine, Pitch
Pine, Red
Pine, Scotch
Pine, Jack
Pine, Western White
Pine, White
Plum, Beach
Spruce, Black
Spruce, Norway
Spruce, Red
Spruce, White

Class III - Species that are not particularly favored but upon which a small proportion of the gypsy moth larvae may develop.

Barberry, European
Bayberry
Birch, Black
Birch, Yellow
Blueberry, Low.
Fern, Sweet
Gale, Sweet
Gum, Black
Hickory, Bitternut
Hickory, Mockernut

Blueberry, Tall
Cherry, Sweet
Cherry, Wild Black
Cherry, Wild Red
Chokeberry
Choke Cherry
Cottonwood
Cranberry, American
Elm, American
Elm, European
Elm, Slippery
Hickory, Pignut
Hickory, Shagbark
Hornbeam, American
Hophornbeam
Maple, Norway
Maple, Red
Maple, Silver
Maple, Sugar
Pear
Poplar, Silver
Sassafras

Class IV - Species that are unfavored food for gypsy moth larvae.

Arbor Vitae
Arrowwood
Arrowwood, Maple-leaved
Ash, Black
Ash, Blue
Ash, Red
Ash, White
Azalea, White and Flame
Balsam, Fir
Blackberry, High.
Blue-flag, Larger
Butternut
Catalpa, Hardy
Cedar, Red
Cedar, Southern White
Cornus
Cranberry-tree
Currant, Red
Cypress, Bald
Dangleberry
Dock, Narrow
Dogwood, Flowering
Elder, American
Eubotrys, Swamp
Feverbush
Grape
Greenbrier
Hackberry
Hardhack, Pink
Hardhack, White
Holly, American White
Honeysuckle, Bush
Huckleberry, Highbush
Inkberry
Ivy, Poison
Juniper, Common
Kentucky Coffee-tree
Laurel, Mountain
Laurel, Sheep
Locust, Black
Locust, Honey
Maple, Mountain
Maple, Striped
Mulberry, Red
Mulberry, White
Osage Orange
Osier, Red
Pepperbush
Persimmon
Privet
Raspberry
Sarsaparilla
Skunk Cabbage
Spine-bush
Sweetbrier
Sweet Pepper-bush
Sycamore
Tea, Appalachian
Tulip-tree
Viburnum, Sweet
Walnut, Black
Willow, Bay-leaved
Winterberry, Smooth

Source: Mosher, F. H., "Food Plants of the Gypsy Moth in America," U. S. D. A. Agriculture Bulletin #250 (Washington, D. C.: Government Printing Office, 1915), pp. 33 & 34.

While lengths of exposure to sunlight seemingly has little, if any, influence on development, an interesting contrast in the effects of temperature on maturation exists. Whereas the Canadian strain shortened its development time to utilize the shorter warm season found in the more poleward locations, development time was decreased by nearly 25 percent in the laboratory resulting from an increase in temperature from 23 °C to 27 °C.[13] More specifically, total development time from egg hatch to adult males (with 5 instars) was 58.77 days at 23 °C and 44.61 days at 27 °C. Males with an additional instar matured in 62.59 days at 23 °C and 48.75 days at 27 °C, closely approximating the usual 6 instar females. However, 7 instar females took the longest time developing, 68.29 days at 23 °C and 50.0 days at 27 °C (for visual comparison see Figure 1).[14] Also, there was a tendency for the pupal weights of the earlier emerging adults to be heavier than those of later emerging adults,[15] thus giving rise to the belief that an increase in temperature of a new environment results in not only the possibility of more than one generation per year but with a higher egg production per generation.

There might be another advantage for the late emerging males since the longevity of males is somewhat shorter than for females. By contrast, the occurrence of later emerging females would be a probable disadvantage since there would be few, if any, available males at that late date.[16] However, since a small percentage of the adult females are indeed of the 7 instar variety (Table II) and since a comparative development rate with 6 instar males exists, the probable adverse effect of late emerging females with no available sires is minimal.

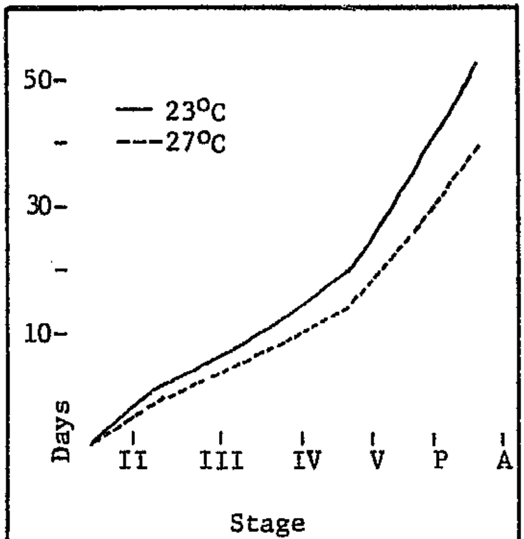

Figure 1A. The effect of temperature on 5 instar males.

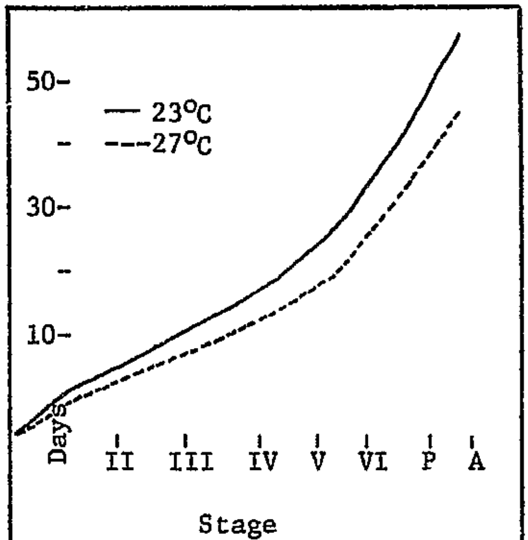

Figure 1B. The effect of temperature on 6 instar males.

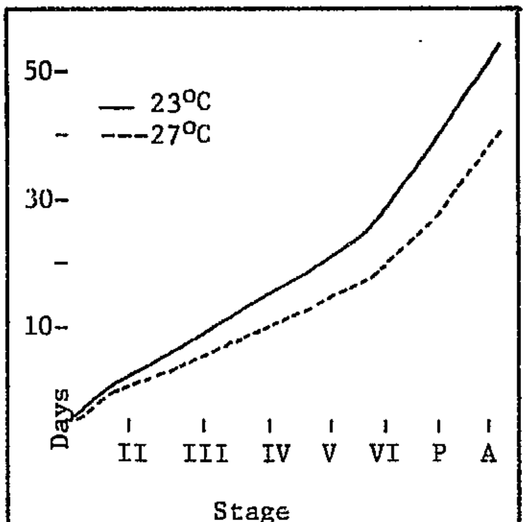

Figure 1C. The effect of temperature on 6 instar females

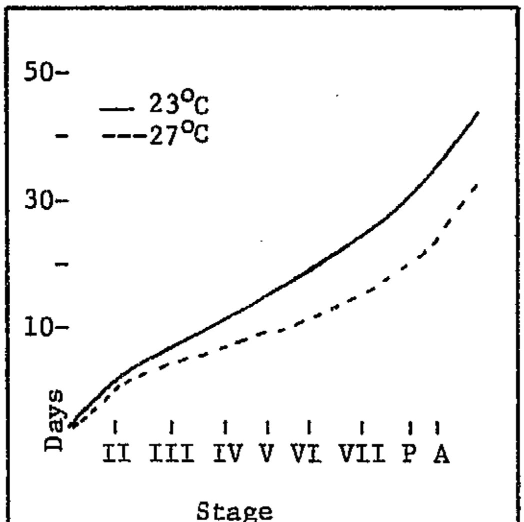

Figure 1D The effect of temperature on 7 instar females.

Figure 1A-D. The Effect of Temperature on Development of Immature Stages of Gypsy Moth Larvae. From D. E. Leonard, 1966, Bulletin #680 of the Connecticut Agricultural Experiment Station, Washington, D. C.

TABLE 2

AVERAGE DEVELOPMENT TIME (DAYS) OF LARVAE FROM ONE EGG MASS REARED UNDER DIFFERING TEMPERATURE AND LIGHT REGIMES

# larval instars	Temp. C	Illumination hrs.	N[1]									
				I[2]	II[2]	III[2]	IV[2]	V[2]	P[3]	Total		
5 Males	23	16	10	8.50	4.70	5.10	5.20	13.50	15.80	52.80		
	27	16	10	6.50	3.80	5.50	5.30	11.50	12.40	45.00		
	27	0	12	6.92	4.50	4.83	5.58	11.25	12.58	45.66		
				I	II	III	IV	V	VI	P	Total	
6 Males	23	16	2	8.00	4.00	6.50	4.00	5.00	13.00	16.00	56.56	
	27	16	1	7.00	4.00	5.00	4.00	5.00	8.00	12.00	45.00	
	27	0	3	6.67	4.00	5.00	4.00	5.00	10.00	12.67	47.33	
6 Females	23	16	8	9.12	4.75	5.00	5.00	6.00	13.62	12.87	56.37	
	27	16	9	6.63	4.22	4.89	4.89	5.33	11.67	10.56	47.89	
	27	0	4	5.25	3.25	5.75	4.50	5.25	12.25	10.00	46.25	
				I	II	III	IV	V	VI	VII	P	Total
7 Females	23	16	3	9.00	5.33	5.33	5.67	4.33	6.00	13.00	12.67	61.33
	27	16	1	8.00	4.00	3.00	3.00	6.00	4.00	13.00	13.00	54.00
	27	0	3	6.00	4.00	4.33	4.33	4.00	4.67	11.33	10.67	49.33

[1]Number of larvae from each test group.
[2]Instar.
[3]Pupal stage.

Source: Leonard, D. E. "Differences in Development of Strains of the Gypsy Moth, Porthetria Dispar," Bulletin of the Connecticut Agricultural Experiment Station, 680 (1966), p. 15.

Beyond these morphological adjustments, perhaps the most significant trait of all is the highly unstable character of the entire population based primarily on food supply until the reaching of the second larval instar. Whereas later instar larvae can survive on most forest tree types excepting a few including ash, tulip-poplar, and sycamore, the young larvae are restricted to feeding on a very few trees (mainly oaks). When the favored hosts are not available to the first instar larvae because of early depletion or a poor egg mass location, they literally take to the wind in search of food.[17]

In summary, the significant adaptive traits of the gypsy moth are: 1) a more than sufficient rate of reproduction, 2) feeding habits which enable it to thrive on a multiplicity of forest types and to discriminate and search out the most beneficial ones, 3) the capability of varying its larval development time to best take advantage of those favorable environmental conditions which are available, 4) the ability to employ man as a vehicle of transport, and 5) the physical construction of the first instar larvae which allows for wind dispersal. Such evolutionary attributes have made the gypsy moth quite a formidable foe. With a position of strength based not only on the usual overpowering numbers of most insect species but also a mobility and adaptive capacity paralleled by few creatures, this pest seems to have very adequately established itself as an intregal part of the ecological scheme of North America.

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[12]Ibid., p. 5

[13]Ibid., p. 30

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[15] *Ibid.*, p. 30

[16] *Ibid.*, p. 21

[17] U. S. Forest Service and Animal and Plant Health Inspection Service, *op. cit.*, p. 1.

CHAPTER III

POPULATION DYNAMICS

As the name obviously indicates, the gypsy moth can be accurately called "the hitch-hiker of the insect world." Its methods of travel are somewhat unorthodox, but they remain very efficient by any standards. The purpose of this chapter is to describe these methods of transport and to analyze just how these abilities to move en masse were obtained, and to analyze historical population movements and the expected trends of population behavior as reported in past observations.

Modes of Population Spread

Quite often egg masses are deposited on automobiles, on campers, and on timber products, all of which serve as transport vehicles for the creation of new infestations. As a result, two major outbreaks have occurred, both in Michigan, which could be directly traced to a camper trailer discovered near the epicenter of the infestation after having traveled through the New England area. Isolated males have also been trapped in other areas such as Florida, Ohio, West Virginia, and Alabama; all being attributed to artificial means. However, new introductions resulting from human-aided transport are expected to be minimal, if not non-existent, in the future as a result of the very intensive quarantine program now in effect.[1]

Natural evolutionary development has enabled the gypsy moth to move into new territory by natural means. Amazingly, wind dispersal serves as the chief means of mass transport although the winged female is totally incapable of flight. The responsibility for mass movement of the populace is borne by the critical instar I stage larvae which are well equipped for air transport due to their light weight (less than one milligram at hatching), their long setae, and their ability to produce silk.[2]

Population density and food supply remain the two primary factors of natural spread. In light or moderate infestations, the young caterpillars climb upward in search of food. Since they cannot identify a host without sampling the foliage, several feeding attempts may occur before a suitable host is found. When large numbers of caterpillars are competing for the same food supplies, those larvae which have found food are continually being bothered by others still searching. This situation persists until very few remain feeding. The longer this condition continues the more nervous and agitated the larvae become until the slightest disturbance causes them to drop from the tree tops on a silk thread, which acts as a sail causing the light weight larvae to be quite easily blown away. With the bulk of the original population having departed, the more mature remnants of the heavy infestation are again able to feed freely, particularly at night when they are less vulnerable to predators.[3]

After once having fed, there is much less chance for larval dispersal because their increased weights prevent their being readily dislodged from their silken mat. However, nutritively deficient eggs from former heavy infestations produce inherently active larvae, even into

instar II stage, which are very easily dispersed by the wind. Although these larvae may be less viable initially, the survivors will, because of an additional instar, produce a more fecund adult. These forms, induced in response to high population density, have less chance for survival, if not dispersed, because of their slower rate of development to adulthood, as well as the competition for the limited food supply.[4] Thus, the cycle of localized population explosion resulting in a mass geographic dispersal is completed.

More specifically, the total period over which windspread of the gypsy moth larvae may be expected is in the range of 27 to 30 days in a normal spring and from 18 to 20 days during the late spring. Ordinarily the maximum dispersion is optimized during 10 to 15 days of high temperatures and favorable winds, usually commencing about two weeks after the first hatching and one week after hatching is complete.[5] Most dispersion occurs at velocities of eight miles per hour or more, but larvae have been found in wind as low as two miles per hour. Since little activity has been observed in cool, rainy weather, the frequency of warm, dry days and the associated predominant wind direction should serve as good indicators of mass population movements in areas of dense population.[6] These factors will be discussed at greater length in a later chapter.

Perhaps even more fascinating than the gypsy moth's ability to become airborne is the tremendous distance traversed. Investigations of Collins (1915) showed that instar I larvae could be blown 21 to 30 miles, occurring at temperatures when the larvae were most active, while Collins and Baker (1934) reported an airplane capture of a larva at 2000 feet elevation. Subsequently, a new outbreak was recorded by Nichols (1962) 35 miles from the nearest known infestation, apparently

resulting from wind dispersal. In addition to their capacity for long distance travel, the gypsy moth larvae consistently move in mass. For instance, in 1961 Campbell observed a higher percentage of dispersal from dense populations with a loss of numbers ranging from 72 per cent to 90 per cent.[7] At this point it would seem that control of the insect by prevention of dispersal through population management in order to maintain sparse populations appears quite feasible in future efforts. However, past attempts to regulate spread have not realized a very high measure of success.

Historical Population Movements

From 1906 to 1912 federal agencies imported natural enemies of the gypsy moth from Europe and Japan, but operations were halted by World War I and were not continued until 1922. However, similar efforts after that date may be described by the adage, "...like closing the barn door after the horse is out." Between 1906 and 1920, the population spread westward against prevailing winds at an average rate of six miles per year, which indicated a series of only localized wind dispersals. During this period, isolated infestations were discovered in New York and in Ohio while the general infestation areas spread to include southern New Hampshire, Rhode Island, eastern Connecticut, southern Vermont and Massachusetts east of the Connecticut River from the original Massachusetts colony.[8]

Aside from this natural spread, a serious outbreak of gypsy moths covering 400 square miles was discovered in New Jersey in 1920 resulting from a new introduction of infested blue spruce trees from the Netherlands. Chemical eradication of the outbreak took eleven years.[9] A graphic illustration of the historical spread is offered in Figure 2.

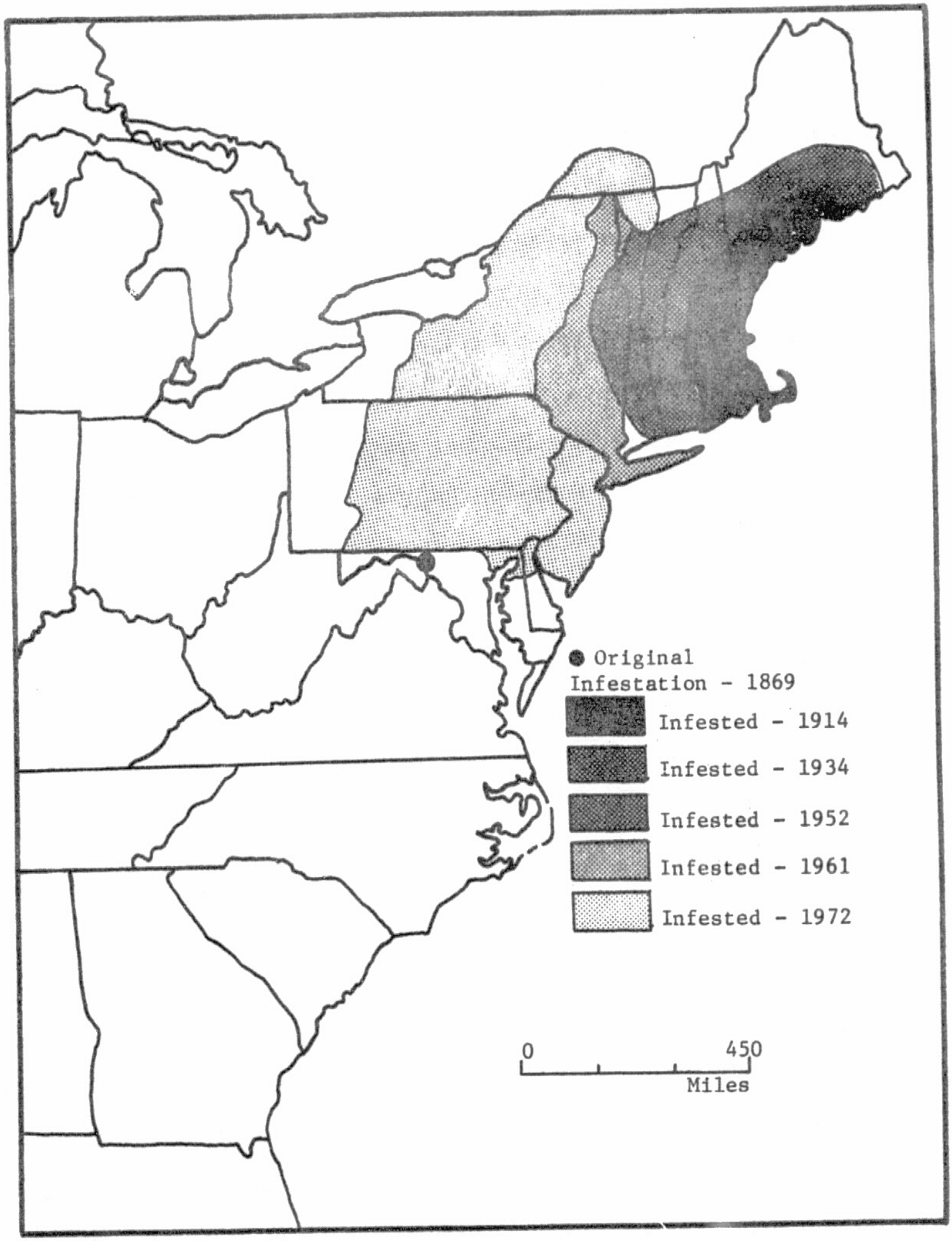

Figure 2. Gypsy Moth Spread (1869-1972). Adapted from Animal and Plant Health Inspection Service, March, 1973

The public has historically played a significant role in the battle with forest pests. Activities of anti-spray groups (mainly against DDT) in New York, New Jersey and Connecticut have been so effective that the gypsy moth has become firmly entrenched in all three states. As a result many times more chemicals must be used in New Jersey, alone, than would have been necessary to completely eradicate the pest ten years ago. In 1958 only 125 total acres were defoliated in all states compared with 1,945,224 acres in 1971. The current breakdown of insect control procedures is permitting other pests to become established in this territory, such as the European chafer which has already invaded New Jersey and is very difficult to control. The European chafer larvae feed on roots of shrubs and grasses; and not being limited to woodlands it is, therefore, a much more potentially serious pest than the gypsy moth.[10] However, the two insects in combination may offer the territory total destructive coverage and may compound the infestation problem. Thus, the trend is set for further geographic diffusion and subsequent destruction.

Sequential Patterns of Population Growth

Commonly, for the first three to five years following the introduction of the gypsy moth into a new area, the insects become generally distributed at low density throughout the region. At this time the moths are only occasionally locally abundant. Following this general distribution, a population explosion may occur throughout the entire area for several years in succession. Eventually, a population collapse occurs followed by a local abundance on the preferred upland oak sites (because

of the existence of younger trees with more tender leaves). On the moist lowland sites, however, an equilibrium occurs as a result of the impact of biological and meteorological control factors (discussed further in Chapter VI).[11]

"These population flushes, which ultimately result in crashes, appear on the surface to be self-destructive. They are probably a necessary event in the population morphology which may have evolved as a consequence of the loss of flight in females. In a sparse population, where suitable food prevails, one might expect that population numbers would increase, dampened only by natural control agents and adverse climatic events. Dispersal would be minimal, limiting genetic recombination. Females are of course flightless, but the earlier emergence of males which do fly would reduce sibling matings to some extent. In logical pockets of low population density, there is probably little gene flow into or out of the clan. As the numbers increase, dispersal is induced prior to the crash of the population. This behavior facilitates genetic mixture and provides the seed for new outbreaks in down-wind areas."[12]

Evidence is available to suggest that the gypsy moth is numerically self-regulating through a shift in the quality of individuals induced by changes in nutrition. This qualitative change affects behavior, developmental rate, fecundity,[13] and dispersal; and this change provides the moth with the ability to respond to both intrinsic and extrinsic factors faster and more efficiently than if dependent on just selection. Adaptability is further enhanced by a change in quality which can be induced either in the previous generation by the amount of nutrient reserves provided the eggs or during the current generation by hunger,

crowding or cool temperatures. This change is best characterized by an increase in the number of larvae with additional instars. In these larvae, a prolongation of instar I and a shift in activity increases their potential for dispersion.[14] Therefore, it can be anticipated that as environmental conditions improve due to migration into new areas, the pest's survival expectancy will be greatly enhanced.

One can safely speculate that, as the gypsy moth is introduced into new areas to the South and West, it will be successful because of an abundance of favored food and a relatively low degree of natural control exerted by native parasites and predators. Apparently, no climatic nor geographic barriers exist to inhibit the spread. An extensive study revealed that the moth might eventually extend its range to include over one hundred million acres, since an abundance of dry and relatively poor (for agriculture) sites occupied by oak stands prevail in the southern Appalachians, in the unglaciated (dry territory) areas of the Midwest, in central Tennessee, and in the Ozarks. Such conditions are highly favorable to gypsy moth build-up.[15]

A southward expansion is indicated by increased male-moth catches in 1971 by sixfold in Delaware, and multiple catches in all but two Maryland counties in the extreme west, while recoveries in Virginia were made at more locations than ever before. At the same time, recoveries were made in such diverse areas as Wisconsin, North Carolina, Ohio, South Carolina and Alabama. A 1972 intensive trapping program resulted in more recoveries in North Carolina, Ohio, South Carolina and Virginia, while first catches occurred in Iowa, Michigan, Tennessee and West Virginia although most cases involved single males at isolated locations and resulted from artificial transport. Michigan was the sole excep-

tion to the rule of isolated discoveries where a several thousand acre infestation was found.[16]

On the basis of suitable host preference, the gypsy moth is expected to eventually occupy the entire region in which oaks are a component of the forest stands. The milder climate is expected to favor gypsy moth development (both morphologically and geographically). As it moves south, egg hatches should occur earlier in the spring, while the larval development time decreases slightly. Thus, the gypsy moth may be capable of producing more than one generation per year, although the development of a second generation in many southern areas remains an uncertain possibility. In addition, evidence is accumulating to indicate that the hardwood forests in the South might be highly susceptible to defoliation, thus experiencing greater mortality than the rate occurring in the Northeast.[17]

A more than sufficient quantity of information has been compiled to suggest that a continuation and probable acceleration in the geographic dispersion of the gypsy moth is not only inevitable but eminent. Such factors as : 1) an evergrowing strength within the gene pool, 2) the existence of a continuous span of susceptible hosts radiating from the area of established infestation, 3) a curtailment in the use of chemical control measures, and 4) the more favorable environs of southerly and westerly habitats, indicate that the gypsy moth is very much a potential resource hazard. A more detailed analysis of predicted population diffusion patterns will be included in Chapter VI.

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[14]"Intrinsic Factors Causing Qualitative Changes in Population of the Porthetria Dispar," op. cit., p. 249.

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CHAPTER IV

ENVIRONMENTAL IMPACT

With the exception of a short time span in the mid 1950's, the gypsy moth has been gradually expanding its territory and simultaneously increasing its destructive capability. While the pest's impact on the environment has been detrimental, it could have been worse if not for one basic inherent weakness, susceptibility to the so-called "wilt disease." This pathogen, caused by a nuclear-polyhedral[1] virus which increases tremendously during moth epidemics, practically wipes out populations over large areas. However, it rarely occurs in light infestations and thus, is ineffective in preventing new outbreaks.[2]

Even in the face of such an adversity as this seemingly built-in population control, the gypsy moth continues its assault on eastern forests and indirectly on their inhabitants. With ever-increasing numbers and with continuously evolving adaptive traits, the gypsy moth's position as a very significant factor to be reckoned with appears confirmed. In this chapter a closer view of this pest's environmental impact will be offered.

Disruption of the Ecological Balance

The adult gypsy moth is harmless, excepting that the female lays 200 to 8,000 eggs at one time on a variety of hosts including trees, rocks, sign posts and the underside of vehicles, especially trailers

and campers. And of course, the result of this activity is either a very expensive suppression program or an accelerated spread.[3] In the latter case, subsequent infestations cause irreparable damage to trees immediately affecting: 1) losses in tree vigor and increment, 2) twig and branch dieback, 3) stunting and immediate defoliation, and 4) tree mortality, depending on the intensity and duration of attack.[4]

Officially, the gypsy moths are now classified as environmental polluters. A single two inch caterpillar eats one square foot of leaf surface every 24 hours; thus, large infestations can easily defoliate an entire forest in a few weeks.[5] These defoliated trees are no longer safe from root rots, bark borers and increased danger of fire. Also, when healthy green foliage which reduces erosion and subsequent silting is removed, the water quality of an area is adversely affected not only from the increased runoff but also from the tons of larvae excrement (a definite organic pollutant) which is readily washed into even potable water supplies. The sudden exposure of fledglings to the hot summer sun due to canopy removal has a deletorious effect on ground inhabitants, not to mention possible localized over-population of reptiles and rodents looking for cooler habitats; furthermore, the potential loss of four tons of terrestrial oxygen from previously healthy forests remains a significant concern.[6]

Aside from this usually incurred damage, more permanent destruction to trees located in near-pure stands may result. Conifers are usually killed in one season if defoliation is complete. However, the probability of this occurrence is fairly low since the pines (which might provide food for later instar larvae) would have to be located near a hardwood forest, necessary for the survival of instars I and II which

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need tender leaves. By contrast, hardwoods may be killed by two successive years of defoliation. However, in most cases one year of defoliation weakens the tree and makes it susceptible to secondary attack by other insects such as the two-lined chestnut borer which killed many oaks after an initial gypsy moth defoliation in New England.[7]

Not all forests are so susceptible to this hazard. Stands containing 50 per cent or less of the preferred host usually sustain little damage. In addition, stands on moist, fertile sites receive less damage for various reasons including hardiness of the trees, advanced age of trees and associated toughness of leaves, and the existence of a favorable habitat for predators such as birds and mice which feed on larvae and pupae.[8]

The adverse effects of a gypsy moth defoliation are varied and many. Their destructive behavior often results in: 1) annihilation of an entire hardwood forest, 2) increased runoff and subsequent erosion from lack of vegetation coverage, 3) a fire hazard enhanced by the existence of numerous dry, dead trees, 4) lost food and shelter for wildlife, 5) the invasion of surburban areas and covering sidewalks, invading homes and buildings, and falling into swimming pools, 6) causing a traffic hazard due to slippery streets in heavy infestation areas, 7) destruction of ornamental shrubs thus decreasing property value, 8) interference of recreation and decreased tourist traffic, and 9) monetary loss from dead lumber and pulp trees.[9]

Damage to Local Economies

After the moths had escaped from the Medford, Massachusetts labratory, the importer requested a few hundred dollars to finance the

hunting down and destroying of the escapees. His plea was refused by the local officials because such measures were deemed unnecessary. Since then, about $100 million have been spent in efforts to control the pest.[10] In its 104 years of residency in North America, the insect has spread over 200,000 square miles from Maine to Virginia and west to central Pennsylvania.[11] Within this range, over 16 million acres have been defoliated to some extent over the past fifty years (for a breakdown by state and year see Table III) with more to come.

Observations of 120 New England woodland plots from 1910 to 1922 revealed that most of the trees were stripped of their foliage two or more times in this period. Results on the predominant species among forty types) varied in cumulative tree mortality: 1) white oak - 58 percent, 2) black and scarlet oak - 46 percent, 3) red oak - 27 percent, 4) gray birch - 55 percent, 5) red maple - 25 percent, and 6) white pine - 26 percent. Overtopped trees were killed in highest numbers and dominant trees, proportionately less.[12] Severe defoliation (60 percent to 100 percent) proved to be the dominant category in a compilation of 1972 (Table IV). Of course, multiple years of such defoliation will invariably result in tree fatilities.

Recent severe defoliation by the gypsy moth on 17,855 acres of the Newark, New Jersey watershed resulted in more than 1,052,000 oaks and 47,600 hemlocks and pines in the 1969 to 1971 period (Table V). White oaks suffered the highest loss of 80 percent while hemlocks and pines fared no better, dying after just one stripping.[13] Table VI illustrates in more detail the proportion of trees in this area per stage of vitality loss.

TABLE 3

SUMMARY OF GYPSY MOTH DEFOLIATION BY STATES

(Calendar Years Beginning in 1924)

Year	Maine	N. H.	Vt.	Mass.	R. I.	Conn.	N. Y.	Pa.	N. J.	Totals
1924	71	591	-	163	-	-	-	-	-	825
1925	-	239	-	48,321	-	-	-	-	-	48,560
1926	1	960	5	78,193	1,663	-	-	-	-	80,822
1927	4,985	3,923	2	131,880	126	4	-	-	-	140,920
1928	5,575	119,757	3	137,121	58	-	-	-	-	262,514
1929	15,187	440,845	-	95,078	23	-	-	-	-	551,133
1930	55,174	205,125	-	27,856	66	5	-	-	-	288,226
1931	20,938	96,690	277	86,694	114	8	-	-	-	204,721
1932	42,298	43,287	1	200,387	376	46	-	-	-	286,395
1933	19,718	216,669	2	157,003	4,292	46	-	-	-	397,730
1934	60,403	285,880	25	128,237	17,750	66	-	-	-	492,361
1935	92,630	330,195	106	106,097	10,908	833	-	-	-	540,769
1936	80,944	192,114	-	152,469	3,095	-	-	-	-	428,622
1937	140,026	72,973	81	393,613	2,063	4	-	-	-	608,760
1938	120,432	34,122	416	154,348	3,297	1,339	-	-	-	313,954
1939	202,193	136,772	5,311	143,292	848	4,224	-	-	-	492,640
1940	204,041	152,797	3,160	125,586	52	-	-	-	-	485,636
1941	122,386	80,579	980	263,369	707	-	-	-	-	468,021
1942	850	6,963	49	36,715	-	-	-	-	-	44,577
1943	10	290	-	34,481	64	-	-	-	-	34,845
1944	21,221	2,346	210	225,637	640	14	75	6	-	250,149
1945	210,881	58,517	93,950	456,832	1,280	16	-	11	-	821,487

TABLE 3--Continued

Year	Maine	N. H.	Vt.	Mass.	R. I.	Conn.	N. Y.	Pa.	N. J.	Totals
1946	203,813	183,943	15,900	217,132	1,645	486	–	–	–	622,919
1947	–	166	–	7,256	–	–	–	–	–	8,422
1948	60	21	–	32,386	–	–	–	–	–	32,467
1949	–	8	–	78,665	–	–	–	–	–	78,673
1950	2	12	–	4,979	–	375	–	–	–	5,368
1951	8,195	2,478	1,108	3,185	–	5,673	675	–	–	21,314
1952	82,715	94,975	26,985	82,372	–	6,005	–	–	–	293,052
1953	174,999	209,335	120,787	917,996	–	56,215	7,745	–	–	1,487,077
1954	170,485	154,015	24,650	118,095	–	13,848	10,355	–	–	491,448
1955	10,810	14,975	8,875	–	–	6,842	10,559	–	–	52,061
1956	7,285	9,305	12,635	3,830	–	3,458	6,645	–	–	43,158
1957	120	–	495	16	–	4,909	858	60	–	6,458
1958	–	–	–	8	–	117	–	–	–	125
1959	1,000	4,000	1,500	382	–	5,980	1,605	–	–	14,467
1960	6,350	4,600	6,132	150	–	15,000	16,490	–	–	48,722
1961	21,340	621	11,834	3,000	–	(not avl.)	30,685	–	–	67,480*
1962	3,998	3,390	6,292	150,000	–	83,290	61,342	–	–	308,312
1963	1,970	8,345	12,020	87,847	–	40,140	22,600	–	–	172,922
1964	–	14,509	23,523	20,787	375	98,552	97,237	–	–	254,983
1965	190	8,451	2,903	17,232	50	86,009	148,366	–	–	263,201
1966	30	20	650	500	110	15,895	34,655	–	5	51,865
1967	825	561	2	909	150	2,731	46,160	–	1,035	52,373
1968	777	5,830	–	3,925	565	16,416	47,525	60	5,025	80,123
1969	1,450	17,160	–	6,060	313	56,881	121,610	830	51,525	255,829
1970	1,080	38,525	–	6,835	1,082	368,706	416,270	10,500	129,835	972,833
1971	820	3,250	790**	18,787	8,525	655,107	479,150	598,200	180,595	1,945,224
1972	40	200	4,215	20,480	22,510	513,880	177,605	404,060	226,140	1,369,130
	2,118,318	3,260,329	385,874	4,986,186	82,747	2,063,120	1,738,212	1,013,727	594,160	16,242,673

TABLE 3--Continued

*Exclusive of Connecticut
**Partial survey

Source: Plant Protection and Quarantine Division, U. S. Department of Agriculture, Moorestown, New Jersey, October 5, 1972.

TABLE 4

GYPSY MOTH DEFOLIATION RECORDED BY STATES IN 1972

	Acres Defoliated			
	Categories of Defoliation			Total
	(Up to 30%) Light	(30-60%) Moderate	(60-100%) Severe	
Maine	40	-	-	40
New Hampshire	160	30	10	200
Vermont	3,920	140	155	4,215
Massachusetts	3,425	2,175	14,880	20,480
Rhode Island	-	20,110	2,400	22,510
Connecticut	340,060*	149,380*	24,400*	513,880*
New York	75,700	26,935	74,970	177,605
Pennsylvania	-	104,910	299,150	404,060
New Jersey	49,335	72,030	104,775	226,140
Totals	472,640	375,710	520,780	1,369,130

* Includes defoliation by the elm spanworm.
Source: Animal and Plant Health Inspection Service, Moorestown, New Jersey, October 6, 1972

TABLE 5

MORTALITY OF OAKS DUE TO DEFOLIATION IN 1969 AND 1970

BY THE GYPSY MOTH ON THE WATERSHED OF NEWARK, NEW JERSEY

Year	Percent Dead	Dead Oaks Per Acre	Total Dead Oaks
1968	6.5	6.5	116,693
1969	14.3	14.3	257,112
1970	38.8	38.5	686,881
1971	58.2	58.9	1,052,195

As with the earlier study in New England, the effects of defoliation by the gypsy moth in the Newark watershed varied among tree species.

Source: U. S. Department of Agriculture, "U. S. D. A.'s Research and Development Gypsy Moth Program" (Washington: Government Printing Office, November, 1971), p. 5.

TABLE 6

PERCENT OF HEALTHY, DECLINING, AND DEAD TREES ON THE WATERSHED OF NEWARK, NEW JERSEY IN 1971 AFTER 2 YEARS OF DEFOLIATION

Tree Species	Healthy 1/	Declining 2/	Dead
White oak	3.3	16.8	79.9
Chestnut oak	11.9	26.9	61.2
Red oak	35.7	28.6	35.7
Black oak	22.9	32.9	44.3
Scarlet oak	27.3	50.0	22.7
Eastern hemlock	43.0	28.1	28.9
Eastern white pines	22.2	58.3	19.5
Red maple	82.1	11.4	6.5
Bitternut hickory	80.3	14.8	4.9
Black birch	94.8	1.0	4.2
Yellow birch	86.9	10.5	2.6
Sugar maple	97.0	3.0	0

1/1 More than 75 percent of canopy alive

2/2 50-75 percent of canopy alive

Source: U. S. Department of Agriculture, "U. S. D. A.'s Research and Development Gypsy Moth Program" (Washington: Government Printing Office, November, 1971), p. 6.

In the summer of 1969, 10,000 oak trees, representing 33 per cent of the oak forest were lost in the Morristown National Historic Park as a direct result of persistent gypsy moth defoliation, a loss of $40,000 in timber value. An equilibrium was expected within three years without any control. However, in every case where the moth showed signs of collapsing after several years of heavy attack, the oak forest has also been depleted.[14]

On a larger scale, losses from tree mortality alone from 1933 to 1952 amounted to an estimated 2,279,819 cord and 128,951,000 board-feet of merchantable timber having a total estimated value of $4,223,556.[15]

More recently, the market value of trees killed by defoliation in New England ranged from more than two dollars per acre of non-commercial woodlands to more than five dollars per acre for commercial forests (1968). These figures did not include the cost of tree removal and replacement. The mortality resulted from two successive defoliations of oak, birch, poplar, willow, linden, apple, pear, and other hardwood types, while one defoliation killed hemlocks and severely damaged the white pines.[16]

At present, moth damage ranges between $2 and $4 million annually through the loss of timber as well as the cost of control measures, and is expected to continue to spiral upward. If the spread reaches the Allegheny, Appalachian and Ozark Mountains, the realm could conceivably engulf over 100 million acres.[17]

Damage inflicted on our environment by the rapid increase in gypsy moth activity has taken its toll in two basic areas: monetary and ecologically. Effect on the total economy is somewhat negligible, but there remains little consolation to affected local communities which

lose millions in destroyed timber and aesthetics (Figure 3 for localized concentrations). Injury to the delicate balance of the physical environment is potentially more devastating with problems being accrued over a period of time and more often than not as a result of directly related secondary attacks. Whichever form the destruction takes, the necessity to control the gypsy moth is a high priority need.

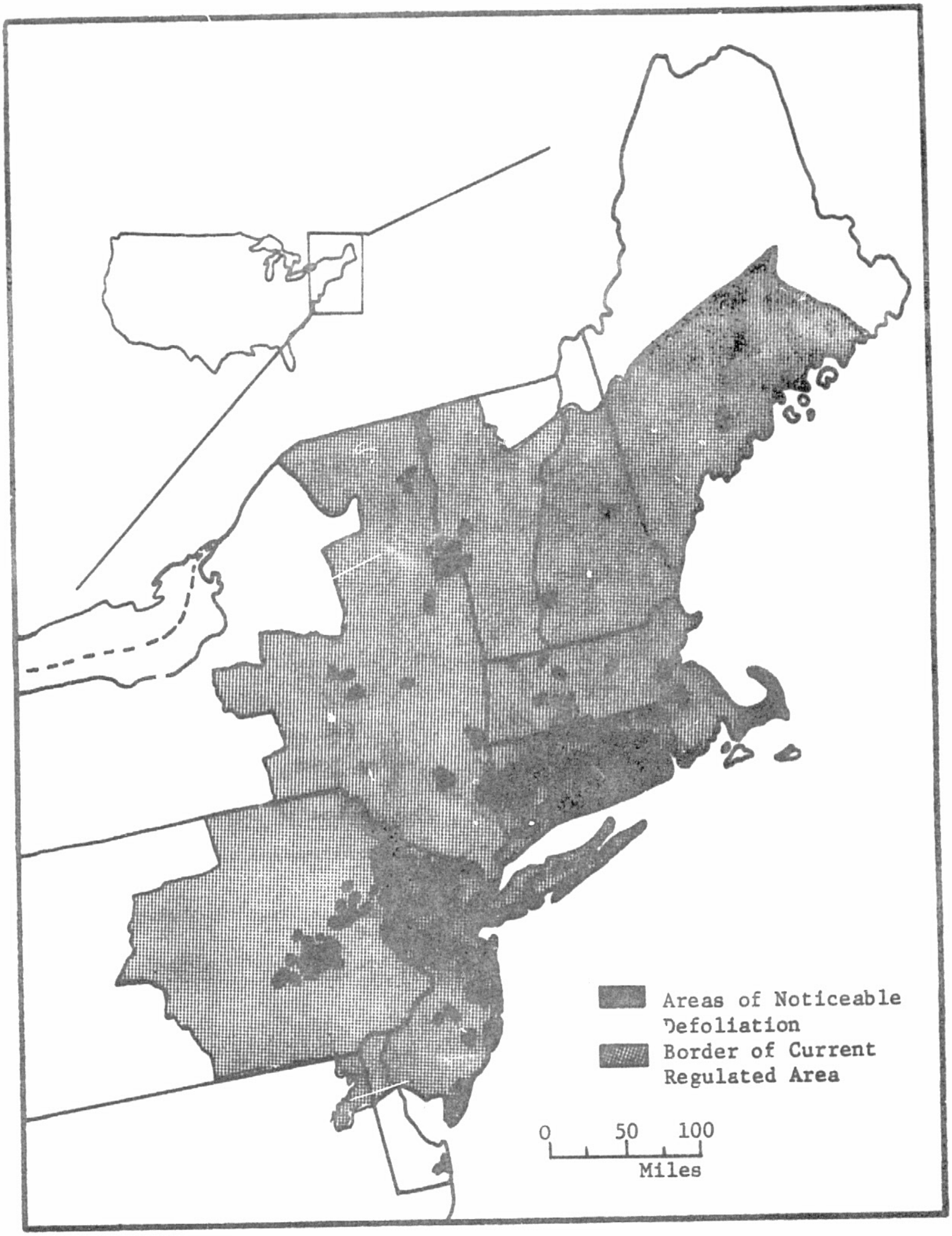

Figure 3. Significant Range of the Gypsy Moth as of 1972. Adapted from the Animal and Plant Health Inspection Service, November, 1972.

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(Chapter IV)

[1]The term "polyhedral" is defined as a geometric figure with many surfaces.

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[3]"Report on Gypsy Moths," Chemistry, Vol. 44 (September, 1971), p. 23.

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[5]John D. Kegg, "The Gypsy Moth--A Vital Concern in the Seventies," New Jersey Forest Pest Reporter, Vol. IV #4 (New Jersey Department of Agriculture-Division of Plant Industry, July, 1970), pp. 3 and 4.

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[7]U. S. Department of Agriculture Forest Service--Southeastern Area, State and Private Forestry Environmental Protection and Improvement, The Gypsy Moth--A Threat to Southern Forests (Washington: Government Printing Office, 1971), p. 6.

[8]Ibid.

[9]John D. Kegg, op. cit., p. 4.

[10]"Report on Gypsy Moth," op. cit.

[11]U. S. Department of Agriculture Forest Service--Southeastern Area, State and Private Forestry Environmental Protection and Improvement, op. cit., p. 1.

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[14]John D. Kegg, "Is the Gypsy Moth an Over-rated Forest Pest?" New Jersey Forest Pest Reporter, Vol. IV #3, (New Jersey Department of Agriculture--Division of Plant Industry, June, 1970), p. 1.

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[16]"Gypsy Moth Activity Continues to Increase," Agriculture Chemistry, Vol. 23 (August, 1968), p. 47.

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CHAPTER V

AVAILABLE CONTROL MEASURES

For almost a century the combined forces of the United States Department of Agriculture and local governments have been waging battle with the gypsy moth. Although many local skirmishes have been won, the overall war has been gradually shifting in favor of the insect. In 1973, when the territorial extension of the infestation is at a record level, the federal government has begun to shift its research and development program for insect control into high gear. "A key part of the management system is a more reliable means of assessing and predicting trends and impacts of populations of the gypsy moth in various ecological situations." Armed with such knowledge, useful manipulative techniques are being developed: 1) a polyhedrosis virus which helps keep population explosions in check, 2) feeding and mating deterrents, and 3) the release of sterile male moths (operational by 1976). However, inferior control tools must be relied on currently: 1) microbial insecticide, Bacillus thuringiensis (Bt), 2) new non-persistent insecticides, 3) disparlure (artificial sex attractant) and of certain parasites and predators.[1]

The significant control agents and facilities for implementation available to those authorities responsible for heading off the anticipated onslaught are enumerated in this chapter. A summary of the

plausibility of each control method and an analysis of the status of the current regulatory program are included.

Responsibility for Control

In 1890 the Commonwealth of Massachusetts created the first state laws requiring the extermination of an insect and set up the legal authority for entering private property for that purpose. Eventually the burden of a single-handed effort was alleviated somewhat when the federal government became active in cooperative gypsy moth control programs and enacted quarantine regulations in 1906.[2] However, the same action time lag which has plagued bureaucracies since their inception, have historically hampered concerted efforts to combat the ever-growing gypsy moth problem. One by one, additional states have, throughout the years, joined the cooperative struggle, but seemingly only after the pest had established itself within their boundaries. However, at this point it would appear that the primary accountability for regulating the gypsy moth has fallen on the federal government.

According to the Federal Plant Quarantine Act of August 20, 1912, and its revisions, shipment of all evergreen products, nursery stock, forest products and quarry products originating within the infested area, as well as tourist traffic, are regulated by the Animal and Plant Health Inspection Service. The conducting of primary research on proposed management of forest pests was to be carried on by the U. S. Forest Service while most actual control activities were to remain joint efforts practiced in conjunction with state agencies within the affected areas.[3]

Imported Enemies

Large scale importations of parasites from Europe and Japan in the periods 1905-1914 and 1922-1933 did not halt the gypsy moth's build-up or spread. Therefore, intensive use of DDT following World War II was implemented and undoubtedly helped keep the insect in check until the 1958 usage (widespread) ban.[4]

Of these early attempts, perhaps the most significant results were realized from the introduction of *Ooencyrtus kuwanai*, an egg parasite imported from Japan in 1908. Adults, surviving the first winter, deposited eggs on host gypsy moth egg masses. Mediocre success of a parasitization of 40 percent to 50 percent frequently occurred in the southern portion of the gypsy moth range, especially in Massachusetts and Connecticut, but a climatic limitation was inherent.[5] *Compsilura concinnata* was later imported and has since become widely distributed throughout the northeastern United States and southeastern Canada. Its parasitization of the gypsy moth in much of the infested area averages 10 percent to 50 percent, but usually toward the lower side of the continuum.[6] In addition, one of the natural enemies from Europe, *Calosoma sycophanta* (beetle) which feeds on the larvae, has been widely introduced but thus far has played an insignificant role.[7]

The absence of efficient predators and parasites has been responsible for past population explosions, but by 1961 two predators and nine parasites were established with marginal proficiency. Also, a virus disease has been introduced but appears only minimally effective. As was the case for the more contempory enemies of the gypsy moth, most of the natural control agents released have failed because they were unable

to cope with the adverse climatic conditions in the North. Many of these factors are currently being re-examined to determine if these agents can survive in the Southeast.[8]

Artificial Eradication Measures

When first instar (especially) larvae are starved in natural conditions, they become active, thus enhancing their spread by wind and prompting the wandering behavior associated with hunger. The result is that the flightless female which remains near the area of pupation will subsequently be depositing her eggs on boulders, on dead trees, on unsuitable host trees, and on other such uninhabitable places. Therefore, limitation of habitat area for the inducement of overpopulation and starvation could work as a preferable controlling agent if properly implemented.[9]

Undoubtedly with this theory in mind, the United States and Canada jointly created a barrier zone from the St. Lawrence River to Long Island along the Champlain and Hudson River Valleys in 1923, encompassing some 10,500 square miles. The area to the east of the zone (generally infested territory) was to be treated by the states and supplemented by the freeing of parasites and other natural enemies by the Bureau of Entomology. All infestations within and to the west of the zone were to be eradicated. For ten years infestations appeared annually within the zone but were held in check. However, in 1932 a serious outbreak occurred in eastern Pennsylvania with only spot infestations being eliminated. Meanwhile, the barrier zone had become generally infested by 1939, and the Pennsylvania infestation persisted. New applications of DDT, commenced in 1944, supposedly wiped out this infestation. However, two

undetected spots remained, and Pennsylvania has been subject to new outbreaks and continual spread of the gypsy moth since.[10] Although the practice of enforced confinement failed, the need for safe biological controls in the face of the alternative toxic chemical application remains of great importance.

The next best (based on safety to the environment) approach seems to be the aiming at an interruption of the insect's life cycle. Elements of such biological control are not intended to be unilaterally implemented but rather to be used in conjunction with one of the other manipulative tools: 1) Nucleopolyhedrosis virus which is a major mortality agent of the moth in dense populations, 2) the use of sterile moths, induced by gamma radiation during the pupal stage, as a confusion factor during mating season, 3) genetic control, 4) stand manipulation, and 5) the use of artificial sex attractants.[11]

The proposed method of genetic control involves the creation of a "strong race" of males with a high incidence of lethal factor genes. These males, when crossed with the American strain females would produce a female progeny of only hydrid individuals that are both sterile and intersexual (tending to female behavior but rarely attracting a male). About 50 percent of the females within the affected group with this trait is expected. The procedure is now in the development stage and is not yet operational.[12]

Perhaps the most ecologically feasible, but not necessarily the most efficient procedure, is that of stand manipulation. This method consists of the removal of favored tree species, especially those of low commercial value or the introduction of more numbers of unfavored

species. This practice is now limited to use in suburban woodlands due primarily to diseconomies of scale.[13]

The use of artificial sex attractants seemingly remains the most popular area of study in the laboratory while offering very poor results in field operations. The most striking benefit from such efforts involves the use of sterile females as bait in an area of uncertain infestation. Since proof exists that attractiveness of both sterile and fertile females to males have been found to be identical, such a method should prove to be quite valuable in the monitoring of population spread.[14]

Synthetic lures have been receiving much attention but as yet remain somewhat questionable. The synthetic homologue, gyplure (similar to natural gyptal, a sex lure) has been sent back to the laboratory for further study since the structure previously assigned to the natural sex pheromone must be considered as incorrect as both appeared to be sexually inert toward the male.[15]

Disparlure, the primary operational artificial sex lure, is considered the most effective especially outside the main infested area. The potentially most advantageous use is in the creation of buffer zones to surround localized spot infestations. This end is achieved primarily by two methods: 1) the confusion method in which the air is permeated with disparlure impregnated on small pieces of cork or other suitable materials leaving the male unable to locate and mate with the flightless females; and 2) the trapping method is merely a means of deploying inexpensive mass-produced traps containing disparlure and a sticky substance which attract and hold males before they are able to find a female and mate.[16]

Although proponents of the use of sex attractants in the control of gypsy moths continue to predict progress in future field operations, historical experiences have been anything but encouraging. In one instance, mating was reduced by 33 percent but on the other extreme it increased by 120 percent, and none of the reduction had any biological significance. In another test to eradicate an isolated infestation by using attractants, baited traps apparently did not hold the population even static during 1971 and 1972. Biologically significant suppression of mating has been achieved with only lab-reared moths and then only with induced confusion by saturation of the air with disparlure, thus jamming the sensory receptors of test males. Any conceivably positive results will be realized sometime in the future.[17]

Discouragingly, the only efficient eradication tools available to combat the gypsy moth are those which will subsequently damage the environment to some extent. For instance, the use of Bacillus thuringiensis (a bacterial agent) has shown no adverse effects on wildlife, birds, mammals, fish, or invertebrates but has been known to completely wipe out a local population of lepidopterous insects.[18]

The only plausible excitement from experiments with insecticides has come from tests with the chemical, carbaryl. But even this approach remains suspect. A risk is present in spraying carbaryl before the entire population of potential gypsy moths has hatched due to a probability of having to respray, whereas a single application will minimize environmental contamination. No instance is known where rain action or runoff has polluted a non-target area with carbaryl residue. Because the amount of material settling into such non-target areas should be small, its effects on the environment should be slight, if any.

Furthermore, the small amounts of contaminants that might reach food plants or livestock are believed not to be detrimental.[19]

By the same token, any carbaryl deposits reaching birds from aerial spraying should have no effects on them individually or their suitability for human consumption. Small residues were found in tissues of cattle, sheep and goats one day after spraying, but after seven days these remnants were eliminated. When fed to mammals, carbaryl is rapidly metabolized and is not stored in the tissue. Also, no effects on reproductive condition and dispersion of mammals has been observed.[20]

In addition to its previously mentioned attributes, a 1971 study in Pennsylvania showed carbaryl to be 90 percent effective in guarding against defoliation, but not necessarily halting population spread due to its failure to reduce egg hatches. It did, however, provide protection against damage in the test area for two years after just one spray. The only major use limitation presently seems to be taking the form of economics. The current requirement is for aerial spraying due to the extensive habitat of the species. Because of this high cost of spray efforts, the primary criterion for determining if an area is to be sprayed is 500 egg masses per acre.[21]

In addition to these economic concerns, a highly significant decrease in soil litter decomposition in the treated area was measured three weeks after spraying, presumably the result of a reduction in microarthropods and other decomposers. The total biomass and numbers of arthropods were reduced more than 95 percent in the treated area (carbaryl) and remained well below that of the control area for five weeks, but after seven weeks total biomass, but not total numbers, returned to the control level.[22] Furthermore, carbaryl is highly toxic

to many species of insects inhabiting the forest, and application for the gypsy moth is likely to adversely affect some beneficial insects. And on the long term basis, phytoplankton productivity was reduced by 16.8 percent in a recent test.[23] Therefore, the ecological implications would, in the long range seem to prompt some rather important considerations.

On a more favorable note, it has been observed that certain tree species are totally ignored by gypsy moth larvae indicating the presence of chemicals that make the foliage unpalatable. Isolation, bioassy and identification of such deterrents may provide non-toxic chemicals to replace pesticides as foilage protectors.[24] But seemingly, the more promising the weapon, the more distant the workable implementation appears to be.

Expected Effectiveness of Control Programs

A population explosion occurred in 1951 and 1952 with over 500,000 acres being defoliated (25 percent to 100 percent of the entire local stands) in the Northeast. This build-up continued until 1957 when saturation spraying of DDT over a three million acre area halted the spread. However, DDT was almost immediately phased out in favor of the currently used carbaryl, and subsequent steady increase in gypsy moth populations has since 1958 occurred.[25]

In any regulatory program, public interest and reaction must be deemed a significant factor. Approximately fifteen years ago, the gypsy moth was believed close to total eradication; that is, until the famous Long Island court battle to halt all aerial spraying took its toll. If plots of land to be sprayed are divided by unaffected areas that may not

be sprayed, an eradication campaign may not be economically feasible, and therefore is not carried out. In other words, if citizens do not want spraying, no spraying is done.[26]

As a result of such imposed handicaps, a drastic change in Department of Agriculture policy has occurred. The current goal has evolved from one of total conquest of the gypsy moth to one of minimizing its spread and reducing the impact of the pest in generally infested areas. Since the 1958 ban on large scale spraying of DDT, noticeable defoliations have surged from a low norm of approximately 80,000 acres in 1968 to 1,940,000 acres in 1971.[27]

Cost of Control

The price of an attempted regulation of any component of our natural environment can be expected to run high. The costs for applying carbaryl alone ranges from $4 to $7 per acre, per spray. While for treatments with Bacillus thuringiensis (the biological control agent) which remains suspect in its effectiveness, the cost is $25 per acre with two applications minimum.[28] These parts of the program do not reflect the total government expenditures in controlling the gypsy moth, but rather serve as an indicator of the tremendous, ever-spiraling costs of the more involved research and development efforts, quarantine program and monitoring spread, as well as the expensive implementation of eradication procedures.

Certain additional costs may not necessarily fall in the monitoring category. For instance, if it were not for the objections of local concerns, a more economically feasible method of restraining the pest might be utilized more often. The most biologically expedient action would be

to sit out the explosion, to permit the gypsy moth to reach an equilibrium in the area and to then eradicate the insect only in those high-hazard, high-resource value stands. To spray these areas for control in toto, however, might have the effect of prolonging the explosion phase. This extension occurs as a result of the impact of the insecticide on the natural predators and parasites. Not only will some of these control agents be killed by the chemical, but by repeatedly eliminating the gypsy moth, these agents have no opportunity to become established in the spray area.[29] Therefore, future experience may just illustrate the futility and waste of our impulsive quick-kill programs, especially in terms of the over-all ecological and financial pictures.

In summary, divisions of responsibility within the federal government's gypsy moth regulation program include: 1) the research and development of artificial sex lures and of invertebrate parasites and predators by the Agricultural Research Service, 2) methods development and federal regulatory activities by the Animal and Plant Health Inspection Service, and 3) research on the biology, ecology and management of the gypsy moth.[30]

The combined efforts of these agencies are designed to produce a control program which will protect the forest resources that are valued for: 1) recreation, 2) esthetics, 3) shade, 4) temperature modification, 5) wildlife habitat, 6) flood control, and 7) timber production; in short, to reduce the fiscal, as well as social costs of the insect.

Still, with the exhaustive efforts of these combined forces, the gypsy moth continues to gradually extend its numbers and range. Thus far, such methods as the creation of a barrier zone, the attempt to

starve the larvae, the use of artificial sex attractants, the importation of predators and parasites, the use of exotic disease organisms, and the development of application of new insecticides have all, in varying degrees failed to halt or hardly slow the seemingly perpetual diffusion. It would appear at this point that without the availability of a workable and ecologically feasible check, the impending assault on new and distant territory is inevitable.

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CHAPTER VI

CHARACTERISTICS OF POTENTIAL MIGRATION

The gypsy moth is an example of an animal whose numbers oscilate within a very wide range, from a few or no individuals per acre of woodland, to massive numbers whose quest for food results in complete defoliation. Therefore, the ability to predict the trend of population dynamics is a prime asset in any sensible control program.[1]

It is toward this end, the prognostication of the moth's geographic diffusion, that this study has been directed. The basis of this chapter is the culmination of efforts to specify and analyze those factors, both inherent and extraneous, which have historically influenced the gypsy moth's propulsive population growth rates and should continue to do so. Just how these conditions should influence future en masse activities, as well as the anticipated results, constitute the primary subject matter of this chapter.

The interaction of natural control forces and the insect in the east central and southern U. S. is expected to produce a pattern of outbreaks similar to that which has been characteristic of the gypsy moth in Europe and paralleled in the Northeast: years of low numbers of the pest followed by sudden flare-ups lasting three or four years.[2] This phenomenon seems to occur consistently with a fair degree of regularity.

Since natural spread of the moth is continuing, the production of forest resources in the eastern U. S. will be affected for many years to come. The proposed action of the combined forces of official regulatory

agencies (1973) would not alter this situation because the program is not presently aimed at preventing natural spread.[3]

Variables of Population Movement

At this point it can be assumed that significant modifying factors do exist, both natural and artificial, which do alter the innate build-up of the total gypsy moth populace. For the purpose of this study it is not necessary to detail the exact degree to which each factor plays a meaningful role, but rather the net effect of each. It is within the scope of this investigation to determine whether each external factor has a positive, negative or neutral effect on the expected population spread.

It has been determined that the most consequential variables of gypsy moth population dynamics include: 1) the velocity and direction of the prevailing winds during the active larval stage, 2) the existence of an unbroken, linear span of preferred hosts, 3) the amount of local relief, 4) the effects of temperatures on the life cycle and larval activity 5) the average number of rainy days for each potentially new infestation area, 6) the effects of artificial transport, 7) the possible existence of natural control agents such as predators or diseases in new habitats and 8) the results of control measures taken by the U. S. Department of Agriculture.

Since the primary mode of massive population movement remains via the wind (2 MPH or greater), the assumption that a favorable predominant wind direction would be a necessity for significant population spread seems a logical contention. However, after viewing Figure 4 (an illustration of average wind conditions for reporting stations within the

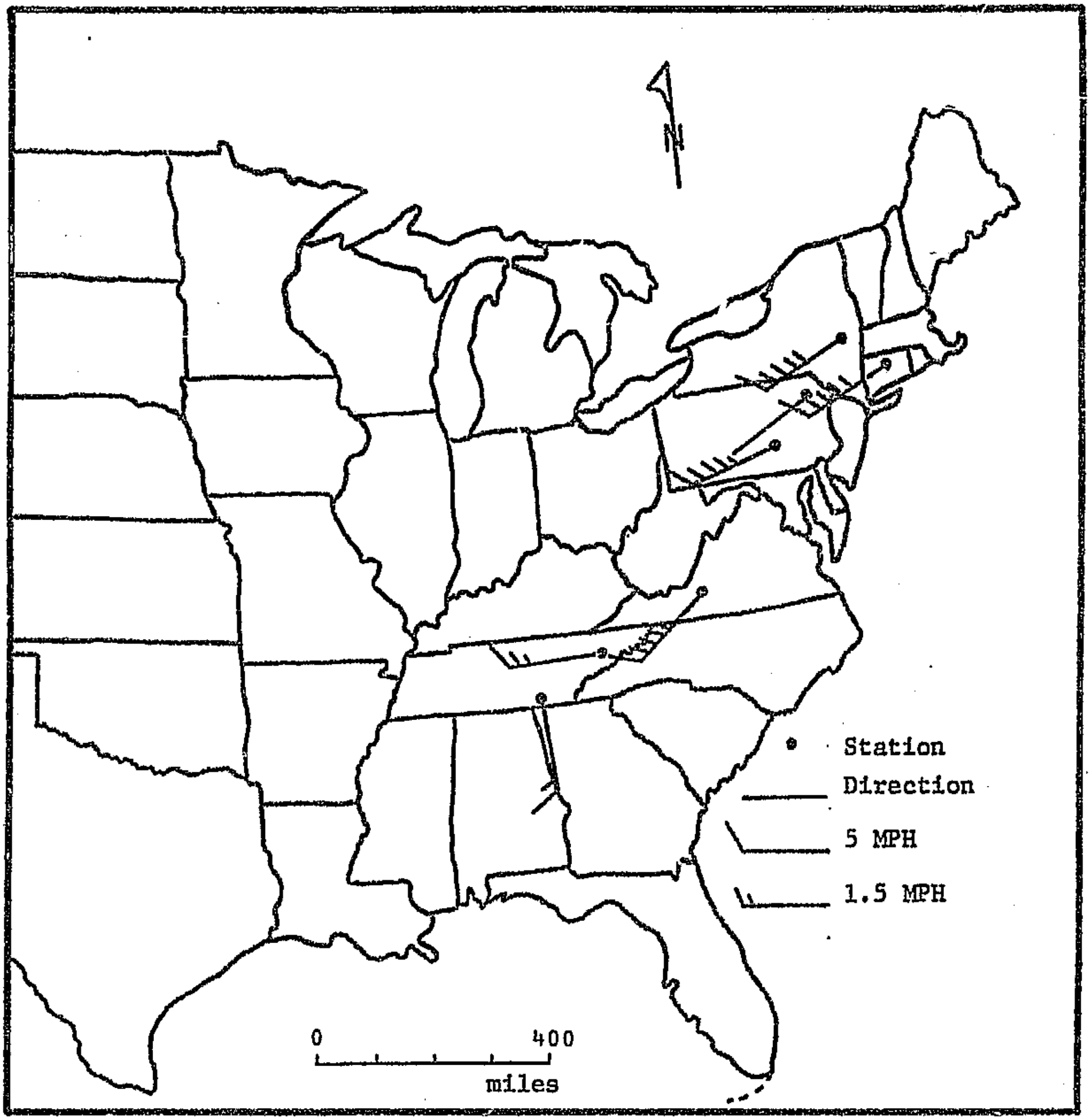

Figure 4. Wind Direction and Velocity for Hartford, Conn., Albany, N. Y., Scranton, Pa., Harrisburg, Pa., Roanoke, Va., Knoxville, Tenn., and Chattanooga, Tenn. (Data from U. S. Weather Bureau).

current infestation area, as well as the anticipated spread corridor) it would appear that if this theory held true, the gypsy would have already perished in the Atlantic Ocean. It must, therefore, be assumed that localized winds and not necessarily the prevailing winds of the region are responsible for gypsy moth transport (only conditions during the month of May for ten years were considered because this is the period of larval instars I and II). Furthermore, a comparison of wind conditions along the proposed southwesterly route of spread within the Valley and Ridge Province (Figure 4) should indicate a striking similarity of average surface winds (for a more in-depth correlation see Table VII). The conclusion that any variance in prevailing wind direction within this zone from North to South would have negligible effects on population diffusion now appears to be a valid one.

Of course, the most important variable of selected habitat has to be the available food supply. Although older gypsy moth larvae can exist on almost any type foliage, instars I and II must rely on the existence of tender broadleaves (primarily beech, black oak, post oak, chestnut oak, red oak, scarlet oak and white oak) for their existence. Not only are these tree species present along the linear span from Pennsylvania to Alabama, but actually represent a very significant component of these forests (Figures 5-11).

As the gypsy moth migrates from its present environment in New England, new climatic conditions will be incurred. As was discussed in Chapter II, temperature represents the most significant and limiting weather factor affecting the gypsy moth life cycle. A northern range limit seems to be the most certain as exposed eggs are unable to withstand temperatures lower than -25 °F., and late spring frosts kill newly

TABLE 7

SUMMARY OF ANNUAL AVERAGE WIND DIRECTIONS AND VELOCITIES ALONG THE ANTICIPATED GYPSY MOTH RANGE

Year	Average Directions	Average Velocities (MPH)
	Hartford, Connecticut	
1963	150°	8.3
1964	210°	9.5
1965	240°	7.9
1966	260°	8.5
1967	330°	11.0
1968	330°	9.4
1969	210°	9.9
1970	210°	9.5
1971	280°	8.2
1972	170°	8.8
10 year mean	239° (WSW)	9.1
	Albany, New York	
1963	160°	8.3
1964	210°	9.3
1965	260°	8.2
1966	250°	10.1
1967	310°	11.2
1968	270°	8.6
1969	210°	9.2
1970	240°	9.5
1971	260°	7.6
1972	210°	8.4
10 year mean	238° (WSW)	9.0

TABLE 7--Continued

Year	Average Directions	Average Velocities (MPH)
	Scranton, Pennsylvania	
1963	210°	8.8
1964	220°	8.5
1965	250°	7.6
1966	270°	8.2
1967	310°	9.0
1968	270°	8.0
1969	230°	9.0
1970	240°	8.7
1971	270°	8.3
1972	90°	9.0
10 year mean	236°	8.5
	Harrisburg, Pennsylvania	
1963	210°	9.2
1964	200°	11.6
1965	270°	8.2
1966	310°	8.5
1967	310°	8.6
1968	260°	8.3
1969	240°	8.1
1970	260°	8.2
1971	300°	7.7
1972	120°	7.8
10 year mean	248°	8.6

TABLE 7--Continued

Year	Average Directions	Average Velocities (MPH)
	Roanoke, Virginia	
1963	180°	9.7
1964	200°	8.1
1965	260°	6.8
1966	220°	8.2
1967	290°	9.0
1968	280°	9.7
1969	230°	8.4
1970	260°	8.5
1971	290°	8.9
1972	50°	7.9
10 year mean	226°	8.5
	Knoxville, Tennessee	
1963	150°	6.8
1964	190°	6.8
1965	250°	5.5
1966	350°	6.8
1967	250°	7.0
1968	250°	6.0
1969	290°	6.5
1970	310°	6.6
1971	270°	7.7
1972	350°	7.3
10 year mean	266°	6.7

TABLE 7--Continued

Year	Average Directions	Average Velocities (MPH)
	Chattanooga, Tennessee	
1963	130°	7.2
1964	180°	6.0
1965	210°	4.3
1966	40°	6.3
1967	260°	7.1
1968	210°	5.9
1969	180°	6.0
1970	180°	5.8
1971	280°	6.7
1972	40°	6.4
10 year mean	171°	6.2

Source: U. S. Weather Bureau

Figure 5. Range of the American Beech. Adapted from Elbert L. Little, <u>Atlas of United States Trees</u>, Miscellaneous Publication #1146, Vol. I (Washington, D. C.: Government Printing Office, March, 1971), p. 125.

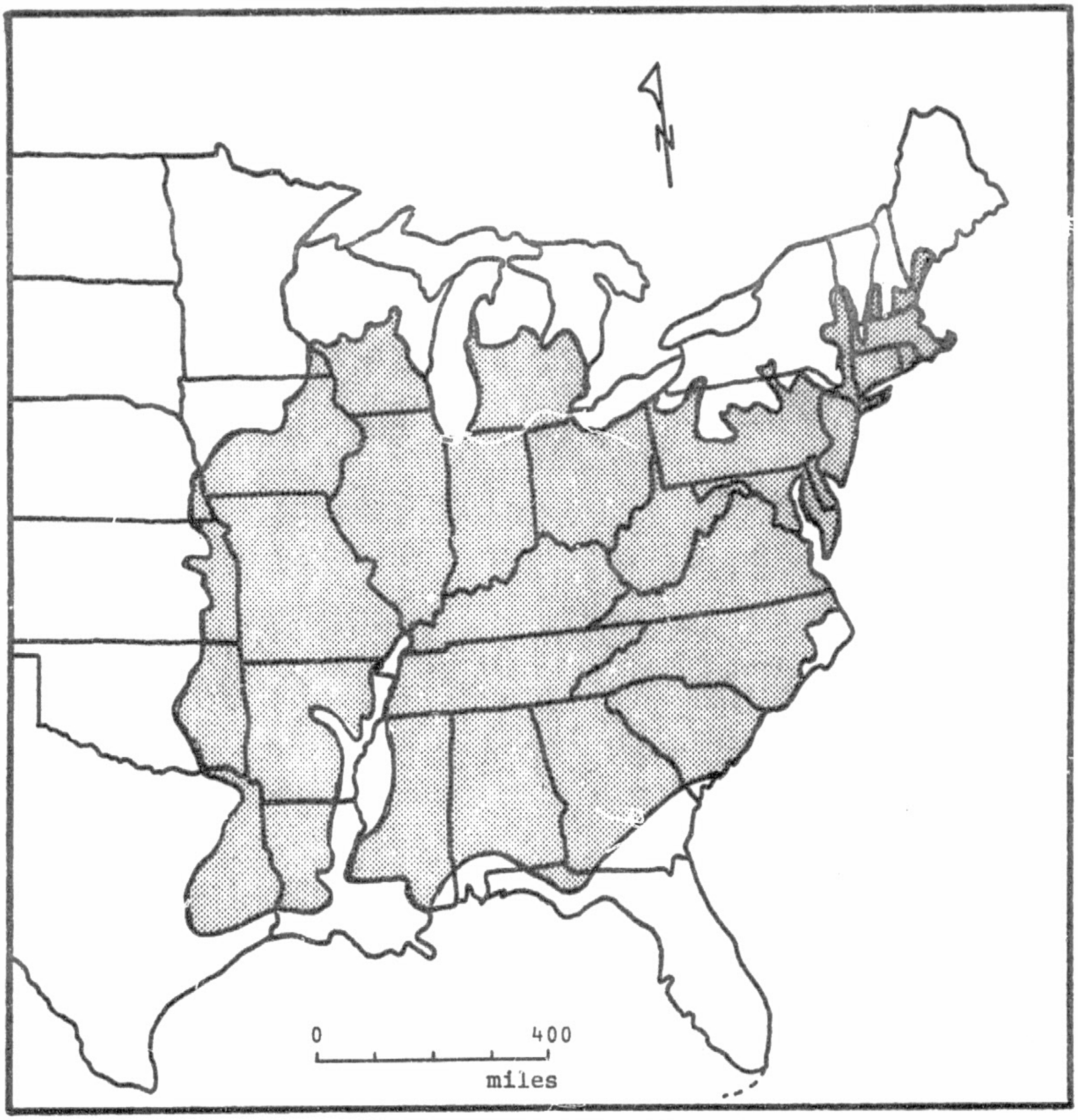

Figure 6. Range of the Black Oak. Adapted from Elbert L. Little, Atlas of United States Trees, Miscellaneous Publication #1146, Vol. I (Washington, D. C.: Government Printing Office, March, 1971), p. 183.

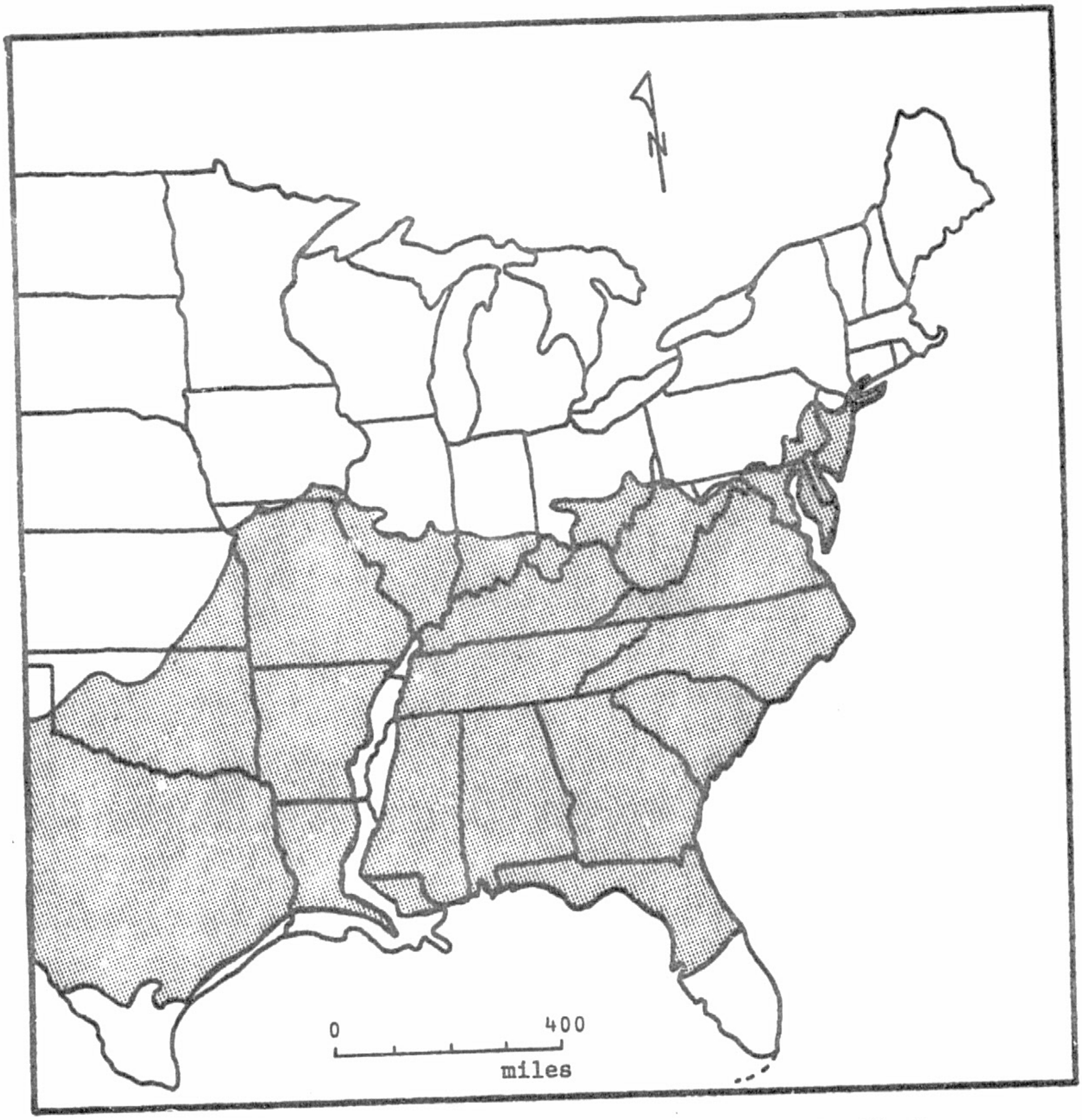

Figure 7. Range of the Post Oak. Adapted from Elbert L. Little, Atlas of United States Trees, Miscellaneous Publication #1146, Vol. I (Washington, D. C.: Government Printing Office March, 1971), p. 182.

Figure 8. Range of the Chestnut Oak. Adapted from Elbert L. Little, Atlas of United States Trees, Miscellaneous Publication #1146, Vol. I (Washington, D. C.: Government Printing Office March, 1971), p. 179.

Figure 9. Range of the Southern Red Oak. Adapted from Elbert L. Little <u>Atlas of United States Trees</u>, Miscellaneous Publication #1146, Vol. I (Washington, D. C.: Government Printing Office, March, 1971), p. 165.

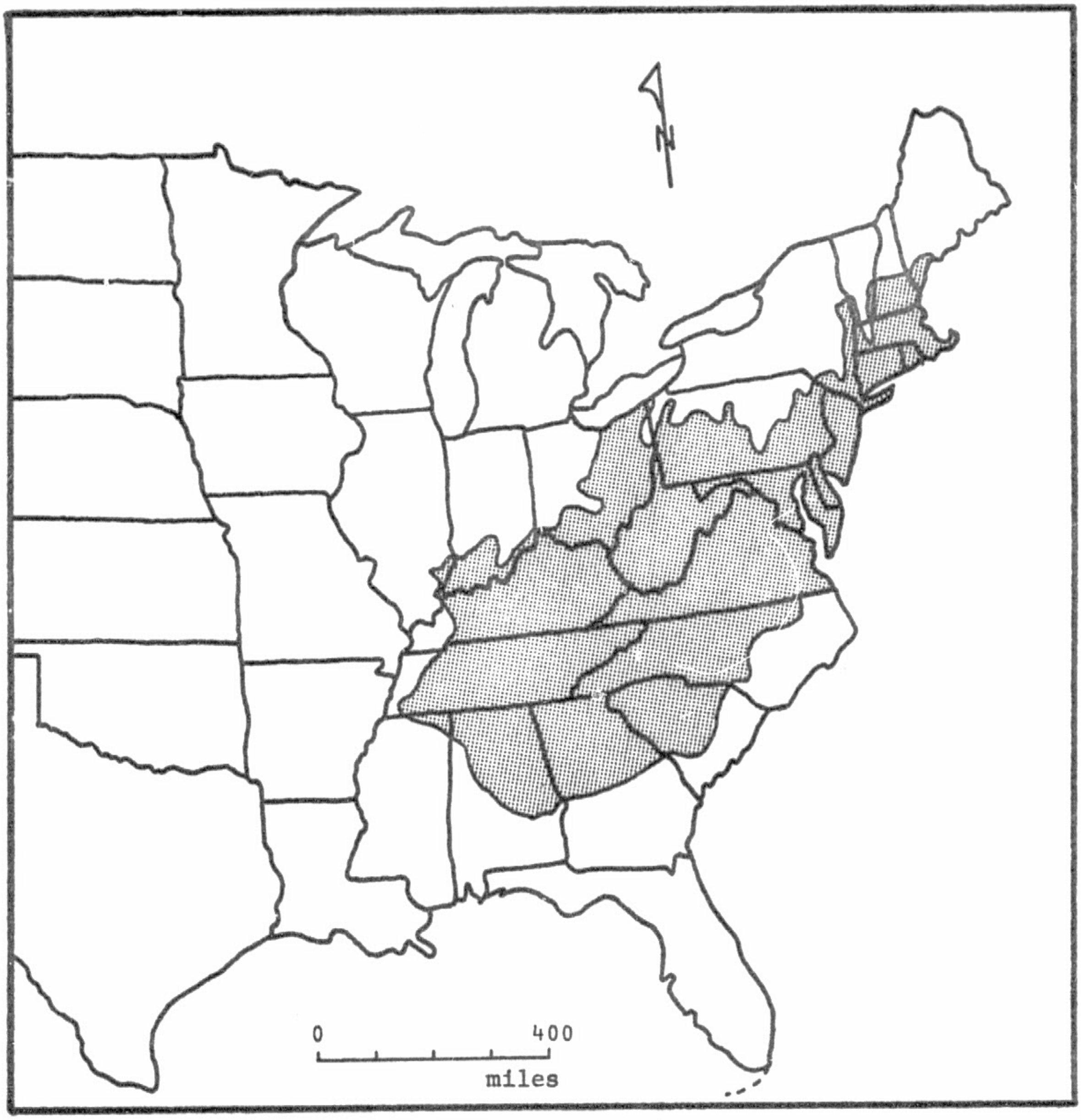

Figure 10. Range of the Scarlet Oak. Adapted from Elbert L. Little, Atlas of United States Trees, Miscellaneous Publication #1146, Vol. I (Washington, D. C.: Government Printing Office, March, 1971), p. 161.

Figure 11. Range of the White Oak. Adapted from Elbert L. Little, Atlas of United States Trees, Miscellaneous Publication #1146, Vol. I (Washington, D. C.: Government Printing Office, March, 1971), p. 157.

hatched larvae.[4] Conversely, speculation that increased temperatures will produce multiple generations of offspring per year remains a fairly widely accepted contention. If indeed this theory becomes fact as the moth migrates southward, it would appear that both population growth and expansion would be greatly accelerated.

To a lesser degree, but still significant, the frequency of rainy days has a direct bearing on the activity of gypsy moth larvae. On days in which precipitation occurs, larvae will usually crawl to the underside of leaves, attach themselves, and are therefore not easily dislodged by the wind. Furthermore, it can be assumed that direct cause-effect relationship exists between the occurrence of precipitation, the amount of precipitation and the frequency of wind dispersals of the instars I and II larvae. Precipitation data for the month of May over a 10 year span (1963-1972) were collected for representative stations within the current and expected infestation areas, and tabulated on the basis of average number of rainy days during the month and the average precipitation occurring during these days (Table VIII). Again, a visual comparison of these data indicates no appreciable variance present. Therefore, the effect of rainfall on the territorial expansion of the gypsy moth as it migrates southwesterly would be insignificant.

As has been discussed in earlier chapters the effect of external control factors, both natural and artificial, have been historically negligible, and indications are that the trend will continue for some time. Predators such as rodents and some reptiles seem to offer a degree of control but are themselves more limited to wet lowlands which are not the best habitat for the gypsy moths' favored hosts (primarily oaks).

TABLE 8

PRECIPITATION DATA ALONG THE

PREDICTED GYPSY MOTH RANGE

Station	Average Days with Significant Precipitation (>.20") in May (1966-1972)	Average Precipation of These Days
Hartford, Conn.	5.14	0.75 inches
Albany, N. Y.	5.86	0.50 inches
Harrisburg, Pa.	6.00	0.52 inches
Roanoke, Va.	5.57	0.56 inches
Knoxville, Tenn.	4.29	0.51 inches
Chattanooga, Tenn.	5.14	0.74 inches
Birmingham, Ala.	5.00	0.89 inches

Source: U. S. Weather Bureau.

While the hand of man has been somewhat instrumental in shaping the past levels of the pest, such a condition is no longer a significant factor of the moth's population spread (at least for the forseeable future). Current eradication and suppression programs are so handicapped that they appear to be currently of little consequence excepting for locally serious outbreaks. This "stalemate" seems to have arisen because it is no longer permissable or ecologically desirable to undertake blanket spray programs for suppression; although, if the value of the threatened resource in a specific area justifies control efforts, the means are available.[5] The one bright spot in man's seemingly insignificant control operations would have to be the quarantine program in which most tourist traffic is checked for possible attached egg clusters. Except for the mid-1950's Michigan outbreak, no appreciable transport of gypsy moths has been discovered.

Delineation of a Natural Corridor to Alabama

A very interesting characteristic of the gypsy moth is its affinity for fairly high elevations, and more specifically the tops of ridges. Whether the reason for this phenomenon is the presence of younger hardwoods with more tender leaves, the absence of most predators or just that ridges happen to intercept wind currents is not yet clear. Whatever the reason, the alternating valleys and ridges (in a northeast to southwest lineation) along the Appalachian Mountains would seem to be target areas for gypsy moth invasion, not only for their favorable environmental conditions but because of their inaccessibility to man and his tools of control. This "natural corridor" of unbroken (no gaps larger than 30 miles which instars I and II larvae have difficulty

traversing) ridges with associated expanses of hardwoods is illustrated in Figure 12.

This display consists of a mosaic of 70 millimeter ERTS-I images (covering approx. 10,000 square miles) which depict the series of linear ridges (a component of the Valley and Ridge Province) spanning the intermediate zone between the current New England infestation and Alabama. MSS (multi-spectral scanner) band 5 was chosen for display purposes because the reflected green (dark areas on the images) received by the scanner in the satellite is the best band for depicting forest vegetation.

It is best to remember that the importance of this expanse of territory is not merely a migration route for wandering gypsy moths, but is in itself a very economically and aesthetically valuable area. The increasing popularity of the Appalachian Mountains for recreation makes the hardwood forested mountain sides a worthy asset. The tourist industry in this region is definitely threatened, at least immediately following the initial gypsy moth invasion.[6]

Prediction of Population Spread

In order to predict any future trend in the diffusion of the gypsy moth, it is necessary to have a good understanding of past phenomena. From viewing Figure 2 on page 23, a pattern of near-radial expansion can be seen with some skewness toward the southwest. There are no known indications which should greatly alter this general trend, except the probable accelerated expansion of populations along the Valley and Ridge Province for reasons already explained.

The first step utilized in projecting the trend of population migration was to define the natural barriers which cannot presently be

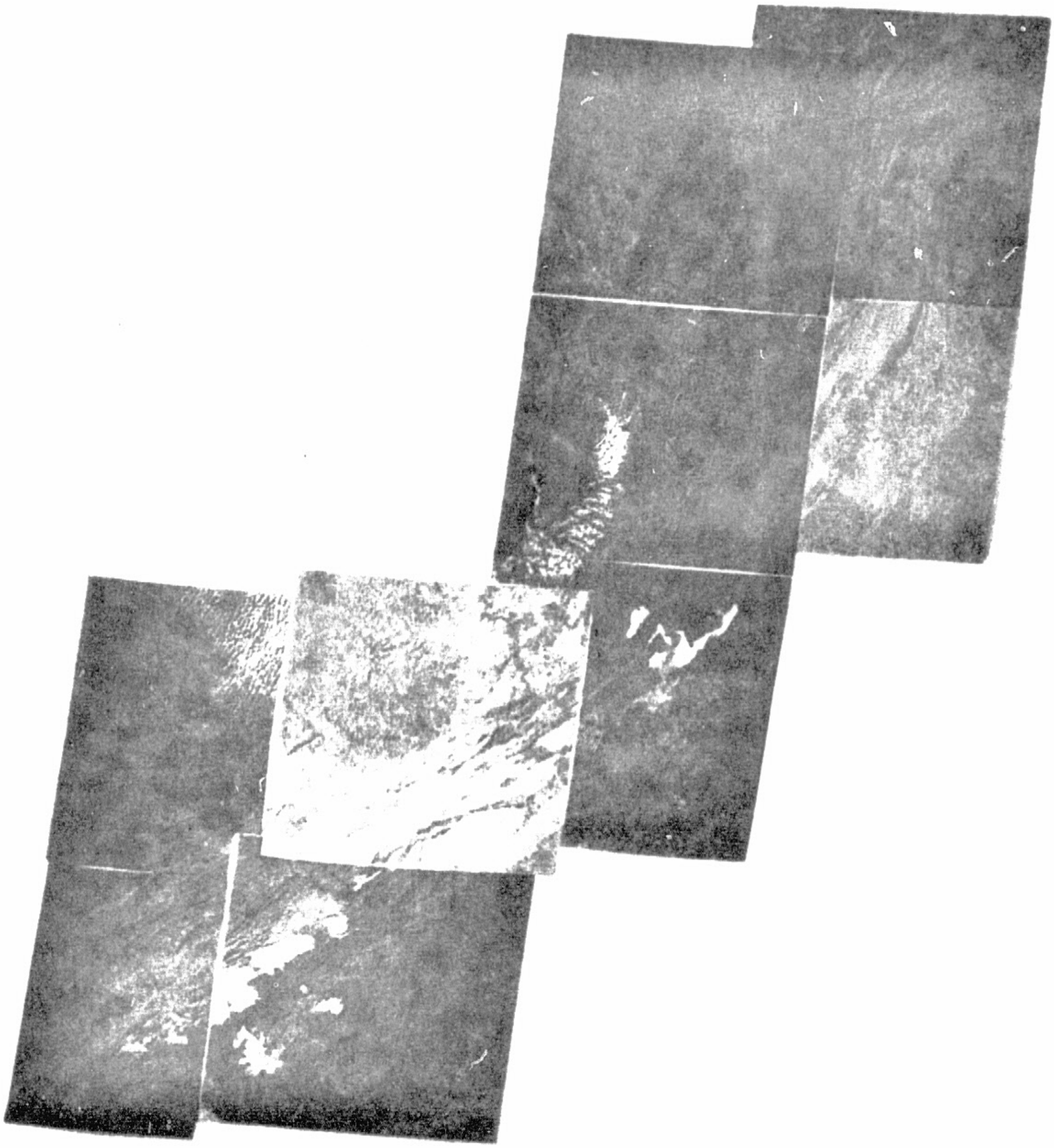

Figure 12. Mosaic of 70mm ERTS Images (Band 5) for Illustration of Valley and Ridge Province.

penetrated by the gypsy moth. To the south of the present infestation area is the eastern edges of the Appalachian Piedmont which intersects the Atlantic Ocean (representing the eastern limits) in Maryland and continues unbroken into middle Georgia. The predominant vegetation type to the east of this region is a pine forest which does not provide food for the fragile instars I and II larvae. The northern limit of the susceptible territory is the boundary of the taiga (coniferous) forest which also approximates the -25 °F. (low temperature) isotherm that if fatal to gypsy moth eggs. For a delineation of this confinement vector, see Figure 13.

It is now, therefore, safe to assume that most future expansion of the moth will have to remain inside these set limits. If concentric circles are drawn radiating outward from the original infestation at regular increments, a series of increases of total area within the expansion corridor can be computed to the point where the last circle intersects Alabama, assuming that the moth will migrate in a consistent linear direction regardless of total area increase within the range. For instance, although the total area within the expansion corridor increases, the rate of directional migration should not be proportionately affected. Therefore, an estimate of total area traversed at the time of the initial introduction of the moth into Alabama will be approximately 535,000 square miles (Table IX).

For the purpose of predicting a future trend it was necessary to separate the moth's history in the U. S. into two divisions, a pre-DDT usage era and a post-DDT usage era. This decision was made on the basis of the obvious depressive effect on population growth during the 1930's and 1940's (Table X) and on the basis of an expected

Figure 13. Assumed Vector of Gypsy Moth Population Spread.
Data from U. S. Department of Agriculture.

TABLE 9

AREAS OF HISTORIC AND PREDICTED

RADIAL EXPANSION OF THE GYPSY MOTH

Area in Circle Radiating from Origin	Angle of Arc	% of Circle	Total Area in Corridor
1 = 43,996 sq. mi.			
2 = 175,986 sq. mi.			
3 = 395,970 sq. mi.	74°	22%	87,113 sq. mi.
4 = 703,947 sq. mi.	69°	19%	133,749 sq. mi.
5 = 1,099,918 sq. mi.	68°	19%	208,984 sq. mi.
6 = 1,583,882 sq. mi.	68°	19%	300,938 sq. mi.
7 = 2,155,840 sq. mi.	68°	19%	409,609 sq. mi.
8 = 2,815,791 sq. mi.	68°	19%	535,008 sq. mi.

TABLE 10

HISTORIC GYPSY MOTH AREA EXPANSION

Years	Area Inhabited (Sq. Miles)	Total Area Increase (Sq. Miles)	Percent Increase	Percent Increase/yr.
1870	100			
1910	4,733			
		74,542	1575%	78.70%
1930	79,275			
		7,473	9.40%	.50%
1950	86,748			
		22,481	25.90%	2.60%
1960	109,229			
		542	.49%	.49%
1961	109,771			
		376	.34%	.17%
1963	110,147			
		794	.72%	.72%
1964	110,941			
		1,515	1.34%	1.34%
1965	112,456			
		1,336	1.17%	1.17%
1966	113,792			
		4,548	3.84%	3.84%
1967	118,340			
		1,790	1.49%	1.49%
1968	120,130			
		5987	4.75%	4.75%
1969	126,117			
		10,513	8.34%	8.34%
1970	136,630			
		24,412	29.12%	29.12%
1971	161,042			
		21,546	33.02%	33.02%
1972	182,588			

Source: U. S. Department of Agriculture.

continuous ban on the insecticide. Therefore, only the data beginning 1960 (the earliest data available after the 1958 ban of DDT general use) was used in the evaluation. If this historic spread data (total growth of infested area from 1960-1972) is plotted on a graph, the point where the extended (via regression analysis) logarithmic curve intersects a line drawn from the 535,000 square mile data point should offer a fairly accurate estimate of the time of introduction (Figure 14). An analysis of the projected geographic diffusion indicates a computed arrival date of the gypsy moth in northeast Alabama within the next 38 years. See appendix B for a summary of this analysis.

However, in order to add credence to this forecast, it was designed as a conservative estimate. If certain previously mentioned variables of population dynamics behave as factors of acceleration as is expected, this prediction of spread rate could be changed to an earlier date. These possibilities could include: 1) the linear ridges of the Valley and Ridge Province could become a more ideal habitat than areas previously invaded, 2) the government's quarantine program could break down, thus allowing for artificial spread, 3) the increasingly shorter duration of rainstorms as one progresses southward could allow for more moth activity, or 4) the possibility of multiple generations per year induced by warmer temperatures. On the other hand if new and efficient control techniques are discovered or if new and presently unknown natural enemies are encountered, the progressive spread might be slowed.

However, based upon past evidence of the impact of control forces on the moth, as well as the historical diffusion rates and direction of the gypsy moth, it is readily apparent that the year 2011 is reasonably acceptable as a target date. But care should be taken not

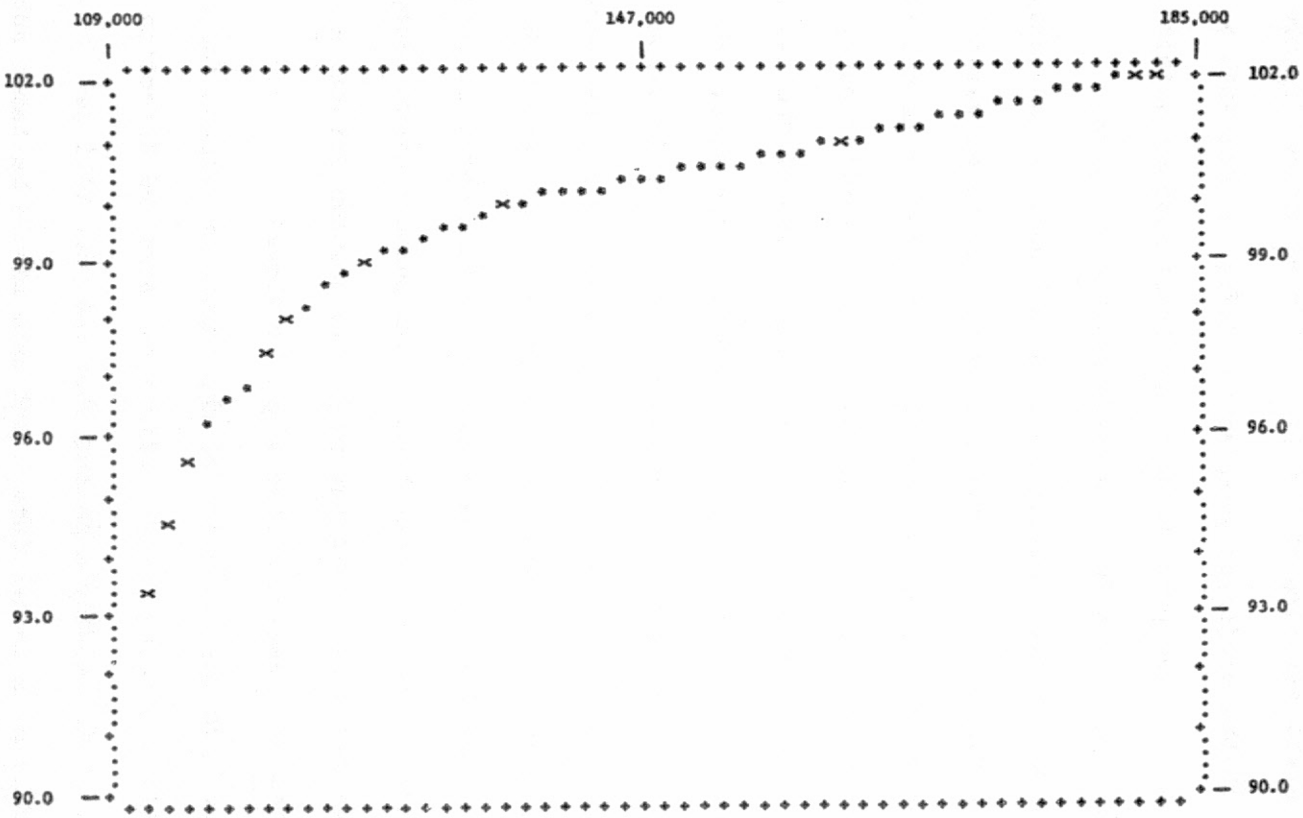

Figure 14A. Plots of Historic Data (1960-1972) Used in Regression Analysis of Potential Gypsy Moth Spread in Total Area.

Area Spread Starting 1960	Years from Original Introduction (1870)
X	Y(X)
109000	89.57748
110433.9	93.35866
111867.9	94.61024
113301.8	95.63309
114735.8	96.20750
116169.7	96.52280
117603.6	96.83807
119037.6	97.38969
120471.5	98.05704
121905.4	98.29654
123339.4	98.53506
124773.3	98.77555
126207.3	99.00858
127641.2	99.14497
129075.1	99.28137
130509.1	99.41777
131943	99.55417
133376.9	99.69057
134810.9	99.82695
136244.8	99.95335
137678.8	100.0430
139112.7	100.1017
140545.6	100.1604
141980.6	100.2192
143414.5	100.2779
144848.4	100.3367
146282.4	100.3954
147716.3	100.4541
149150.3	100.5129
150584.2	100.5716
152018.1	100.6303
153452.1	100.6891
154886	100.7478
156319.9	100.8066
157753.9	100.8653
159187.8	100.9240
160621.8	100.9828
162055.7	101.0470
163489.6	101.1136
164923.6	101.1801
166357.5	101.2467
167791.4	101.3132
169225.4	101.3798
170659.3	101.4464
172093.3	101.5129
173527.2	101.5795
174961.1	101.6460
176395.1	101.7126
177829	101.7791
179262.9	101.8457
180696.9	101.9122
182130.8	101.9788
183564.8	102
184998.7	0

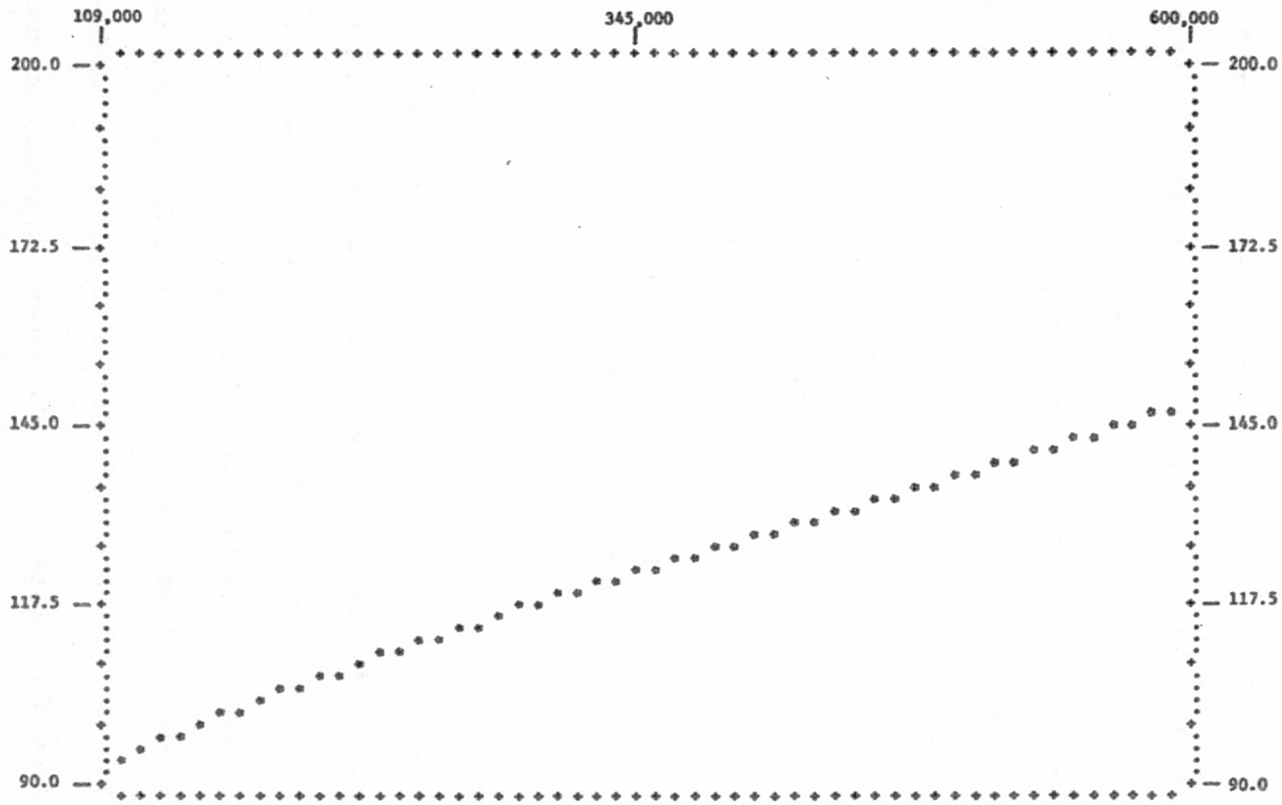

Figure 14B. Regression Analysis Projecting the Trend of Historic Data (1960-1972) of the Gypsy Moth Spread in Total Area.

Area Spread Starting 1960 X	Years from Original Introduction (1870) Y(X)
109000	93.97401
118264.1	95.33925
127528.3	96.65944
136792.4	97.94087
146056.5	99.18253
155320.6	100.4069
164584.8	101.5990
173848.9	102.7579
183113	103.9160
192377.1	105.0453
201641.3	106.1577
210905.4	107.2545
220169.5	108.3372
229433.6	109.4069
238697.8	110.4647
247961.9	111.5114
257225	112.5420
266490.1	113.5759
275754.3	114.5931
285018.4	115.6030
294282.5	116.6051
303546.6	117.6000
312810.8	118.5881
322074.9	119.5697
331339	120.5452
340603.1	121.5151
349867.3	122.4795
359131.4	123.4388
368395.5	124.3932
377659.6	125.3430
386923.8	126.2883
396187.9	127.2295
405452	128.1667
414716.1	129.1000
423980.3	130.0297
433244.4	130.9559
442508.5	131.8787
451772.6	132.7984
461036.8	133.7149
470300.9	134:6285
479565	135.5392
488829.1	136.4473
498093.3	137.3526
507357.4	138.2555
516621.5	139.1559
525885.6	140.0540
535149.8	140.9497
544413.9	141.8433
553678	142.7348
562942.1	143.6242
572206.3	144.5116
581470.4	145.3972
590734.5	146.2808
599998.6	147.1527

to be overly optimistic about that distant date. The factors listed above may have a net effect of greatly speeding or slowing the migration of the insect. In other words, governmental agencies, as well as the Alabama public should not be lulled into the assumption that 38 years may be available to effect a deterrent.

Alabama Target Areas

Since the expected migration of gypsy moths into Alabama in the near future appears inevitable, it would now be proper to survey the possible impact of such an invasion. Figure 15 illustrates the fact that all of Alabama with the exception of the cedar glades, will be eventually vulnerable to attack with a proportion of a least 50 percent oak as a forest component (the major criterion of susceptibility). The best indicator of susceptibility, the white oak, makes up a significant portion of the forest in every county but four in south Alabama and one in the north (Figure 16). Furthermore, the significant presence of preferred hardwood hosts can be found in almost every county in the State (Figures 17-20). Through a correlation of these maps of Alabama hardwoods with maps of susceptible conifers, mainly hemlock and white pines (Figures 21 and 22), they appear definitely in danger of attack because of their close proximity to hardwoods which are necessary for the survival of young larvae. These softwoods, which remain quite important to the paper industry are among the favored foods of later instar larvae which do the majority of the actual defoliating.

Because of the obvious susceptibility of the entire state of Alabama and the great amount of time necessary for completion, it has been deemed unnecessary to undertake the production of a map of all hardwood forests in Alabama from ERTS imagery for this study. Instead, an analysis

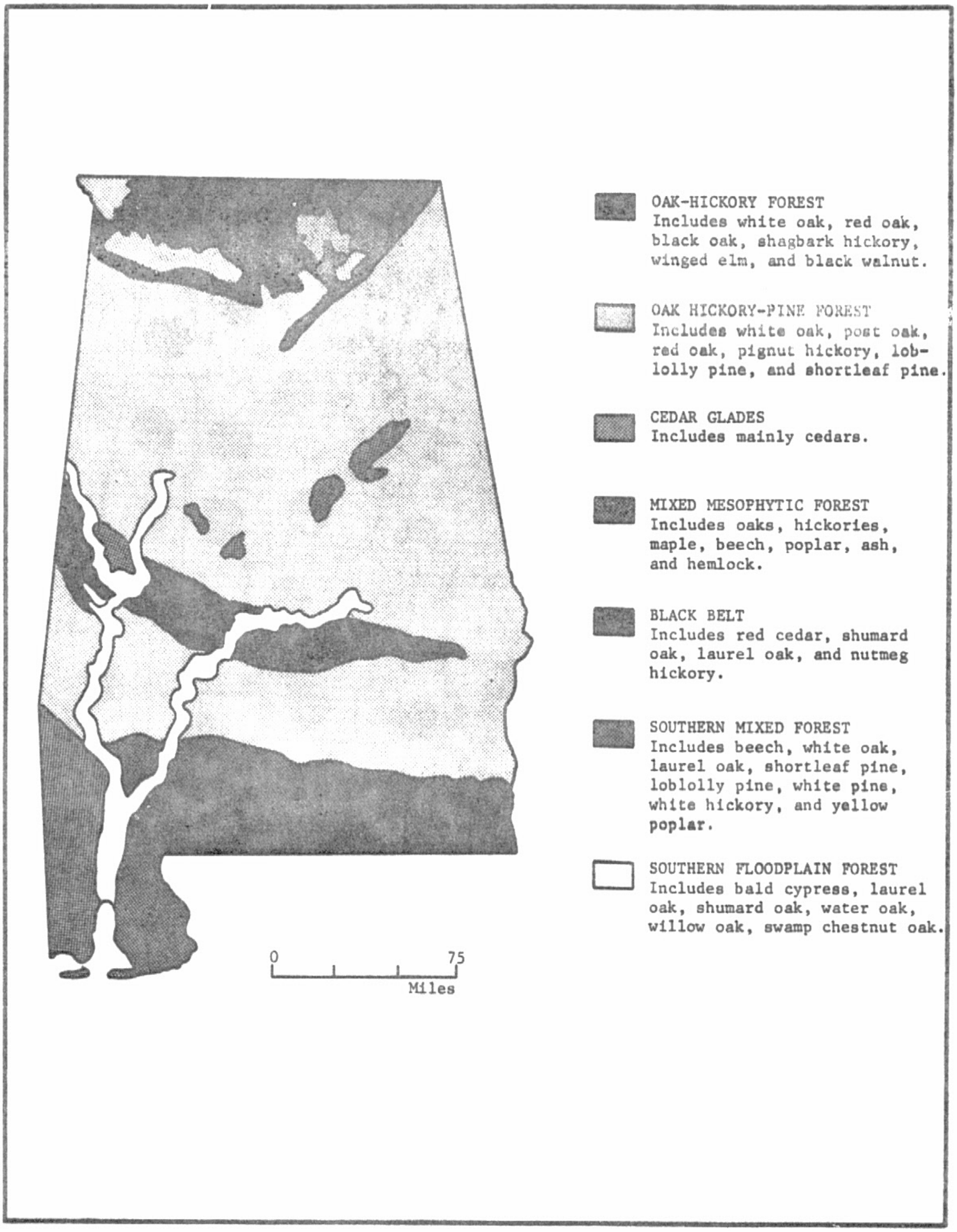

Figure 15. Forest Types in Alabama. Adapted from A. W. Kuchler, The National Atlas of the U. S., Department of Interior (Washington, 1970), p. 91.

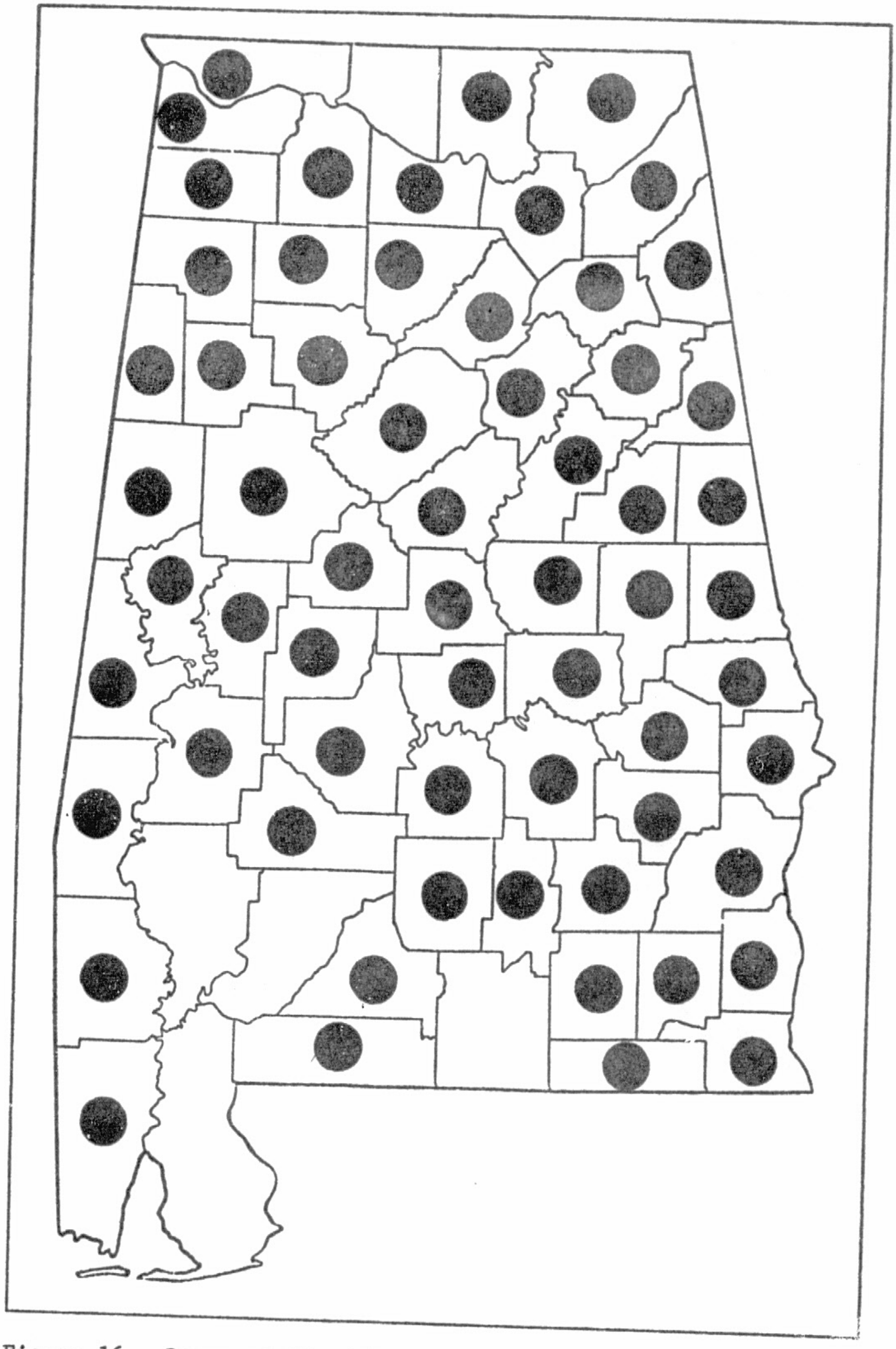

Figure 16. Range of Significant White Oak Presence in Alabama. Adapted from Ross C. Clark, The Woody Plants of Alabama (St. Louis, Missouri: Missouri Botanical Garden Press, 1972), p. 151.

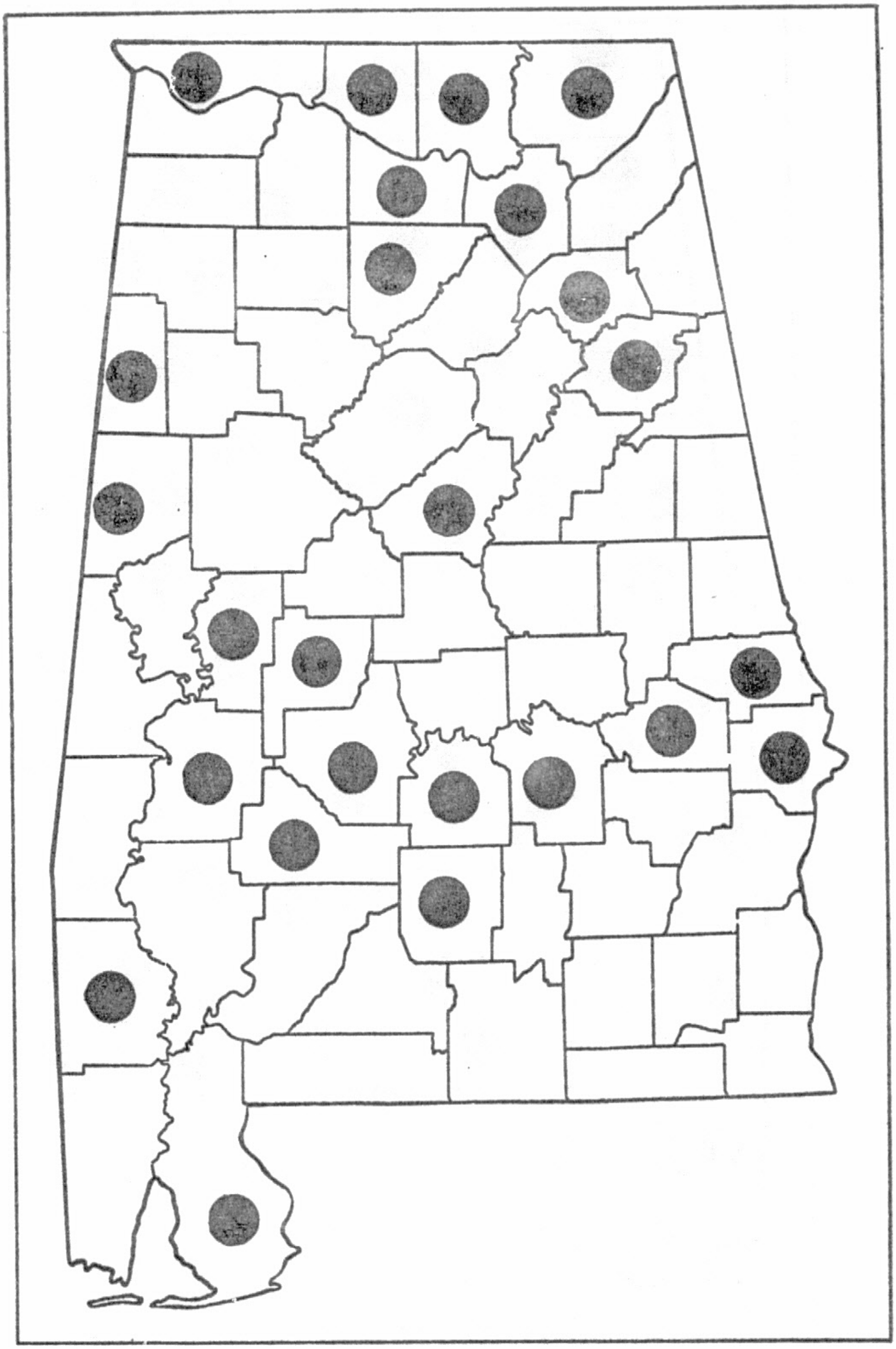

Figure 17. Range of Significant Red Oak Presence in Alabama. Adapted from Ross C. Clark, The Woody Plants of Alabama (St. Louis, Missouri: Missouri Botanical Garden Press, 1972), p. 155.

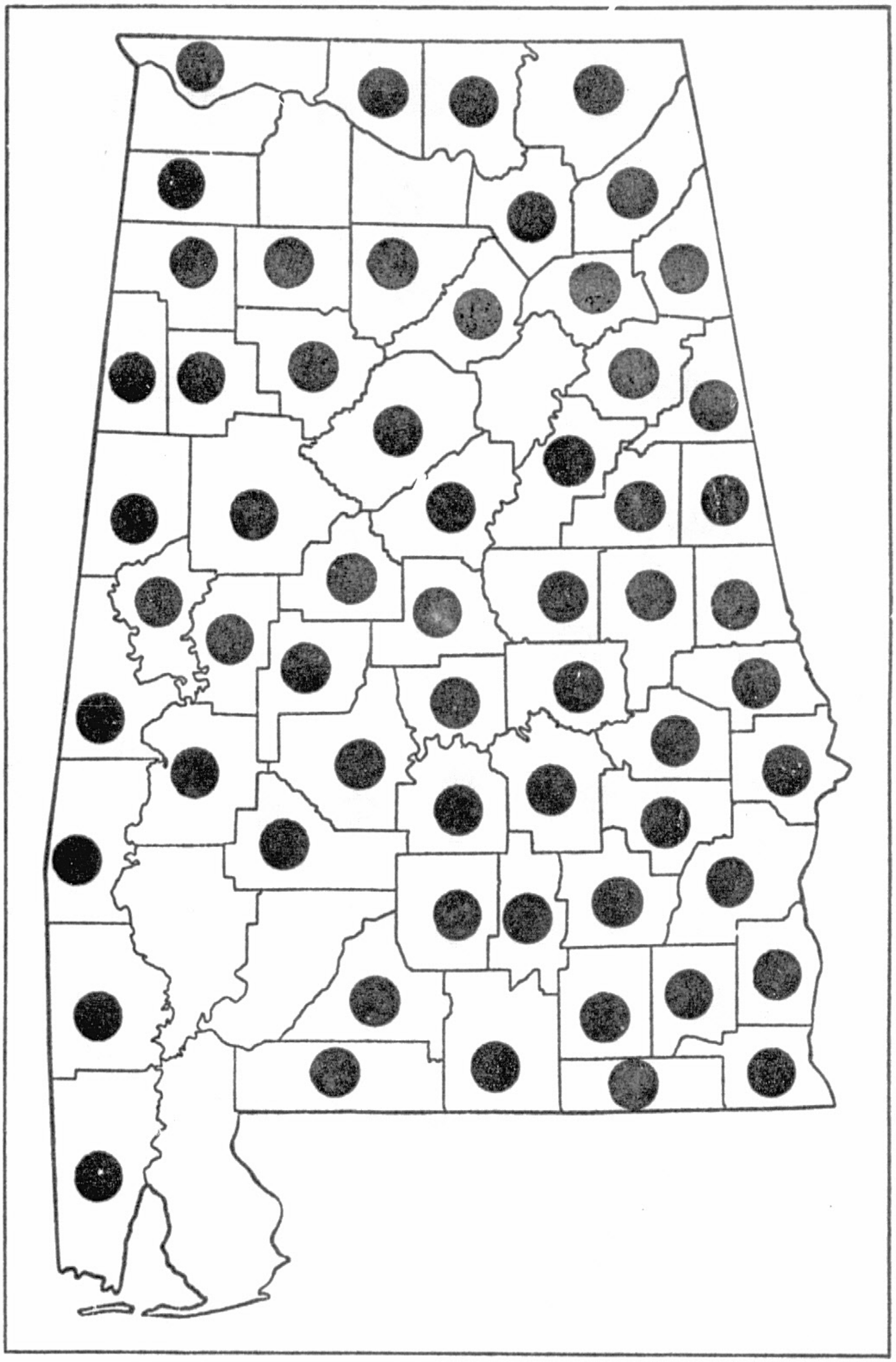

Figure 18. Range of Significant Birch Presence in Alabama. Adapted from Ross C. Clark, The Woody Plants of Alabama (St. Louis, Missouri: Missouri Botanical Garden Press, 1972), p. 149.

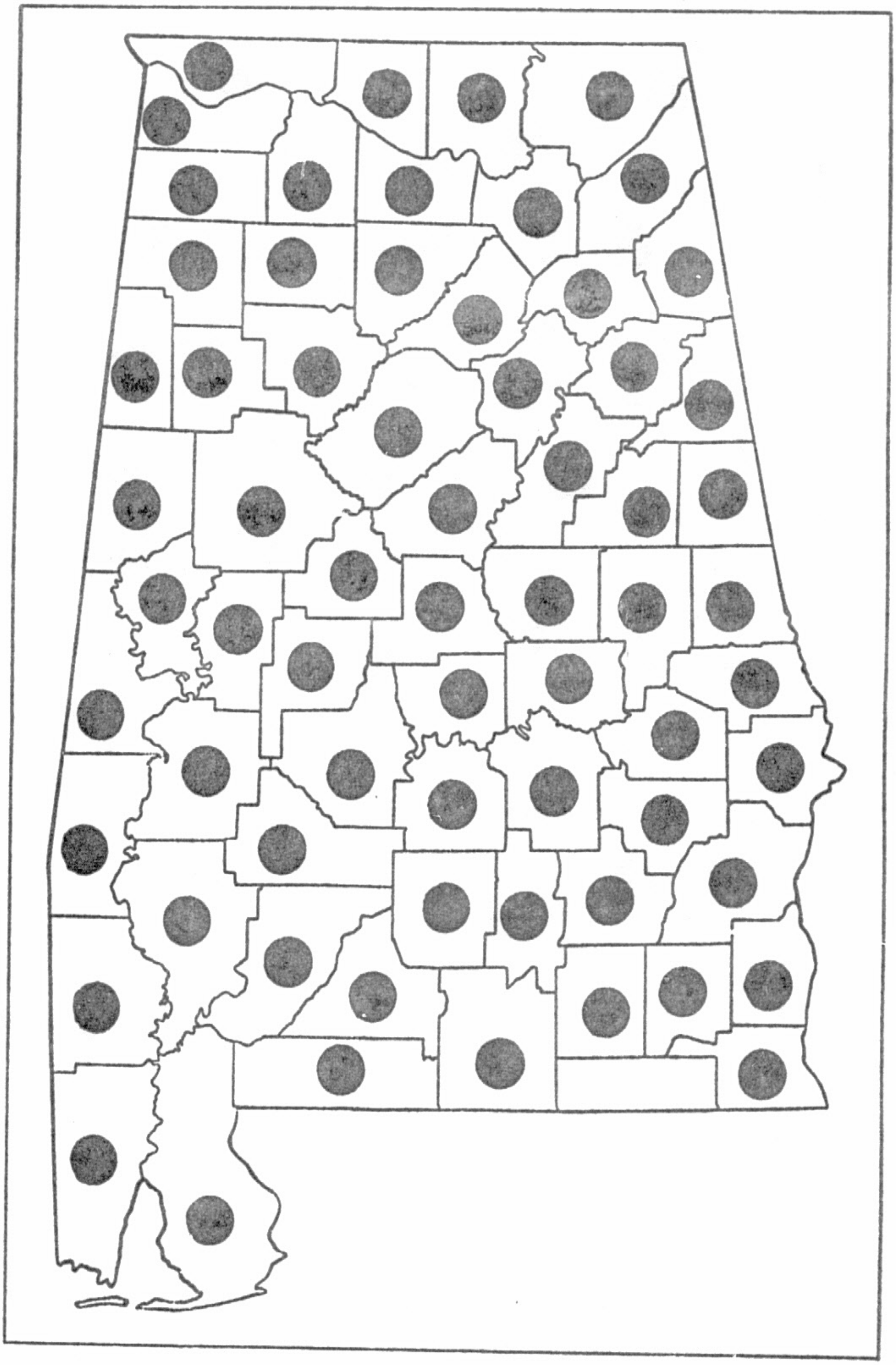

Figure 19. Range of Significant Beech Presence in Alabama. Adapted from Ross C. Clark, The Woody Plants of Alabama (St. Louis, Missouri: Missouri Botanical Garden Press, 1972), p. 151.

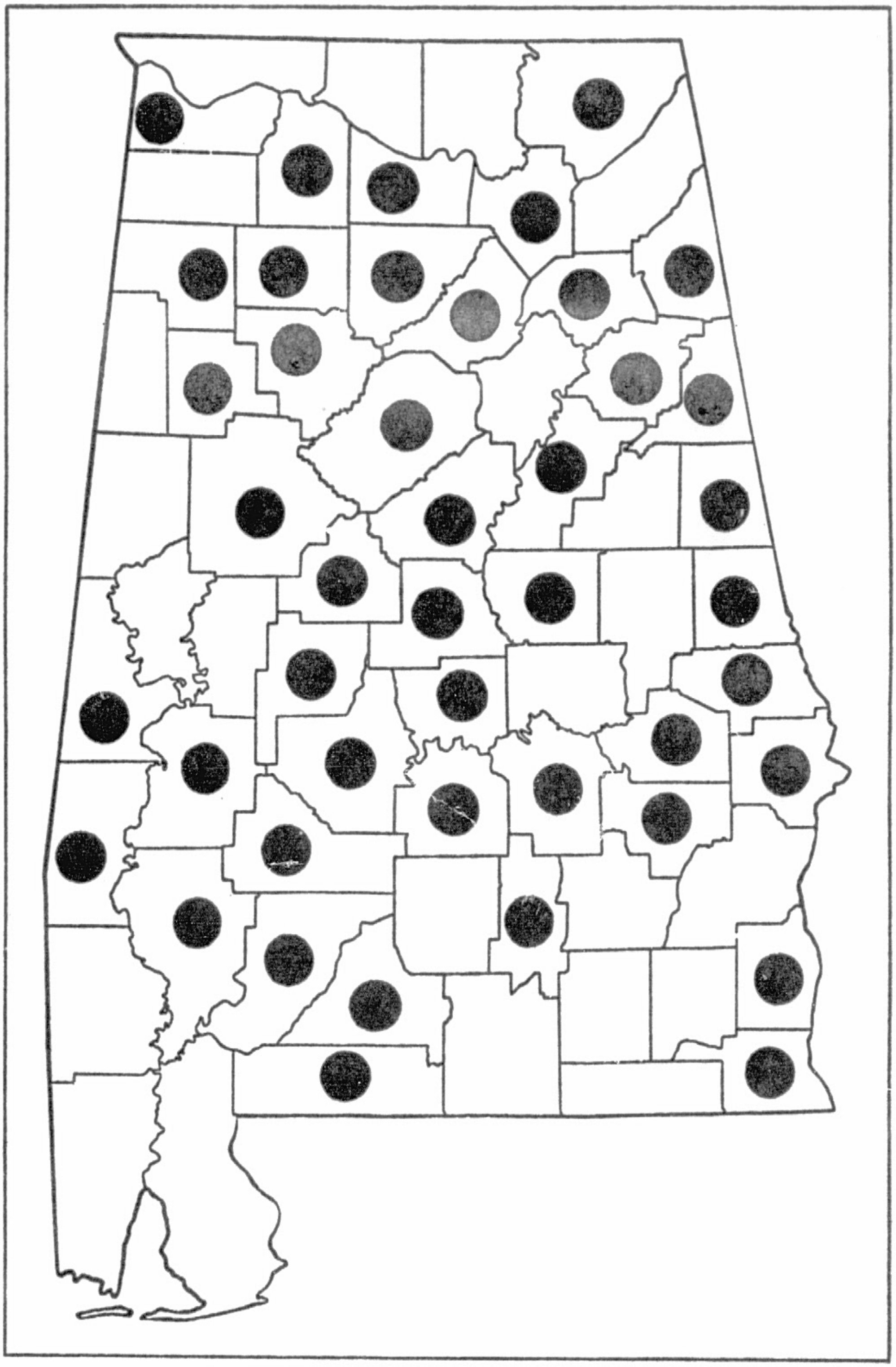

Figure 20. Range of Significant Linden Presence in Alabama. Adapted from Ross C. Clark, The Woody Plants of Alabama (St. Louis, Missouri: Missouri Botanical Garden Press, 1972), p. 206.

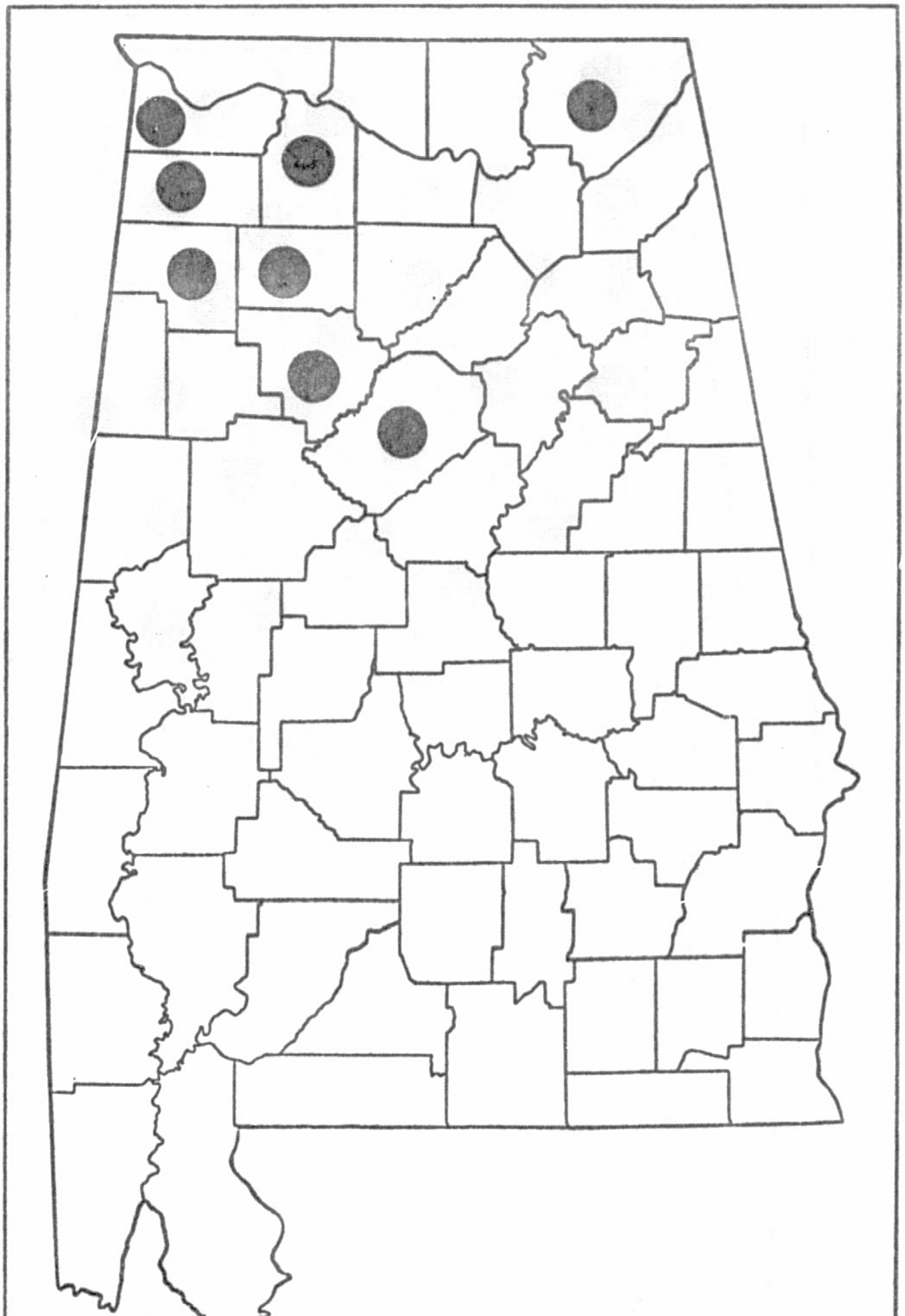

Figure 21. Range of Significant Hemlock Presence in Alabama. Adapted from Ross C. Clark, The Woody Plants of Alabama (St. Louis, Missouri: Missouri Botanical Garden Press, 1972), p. 137.

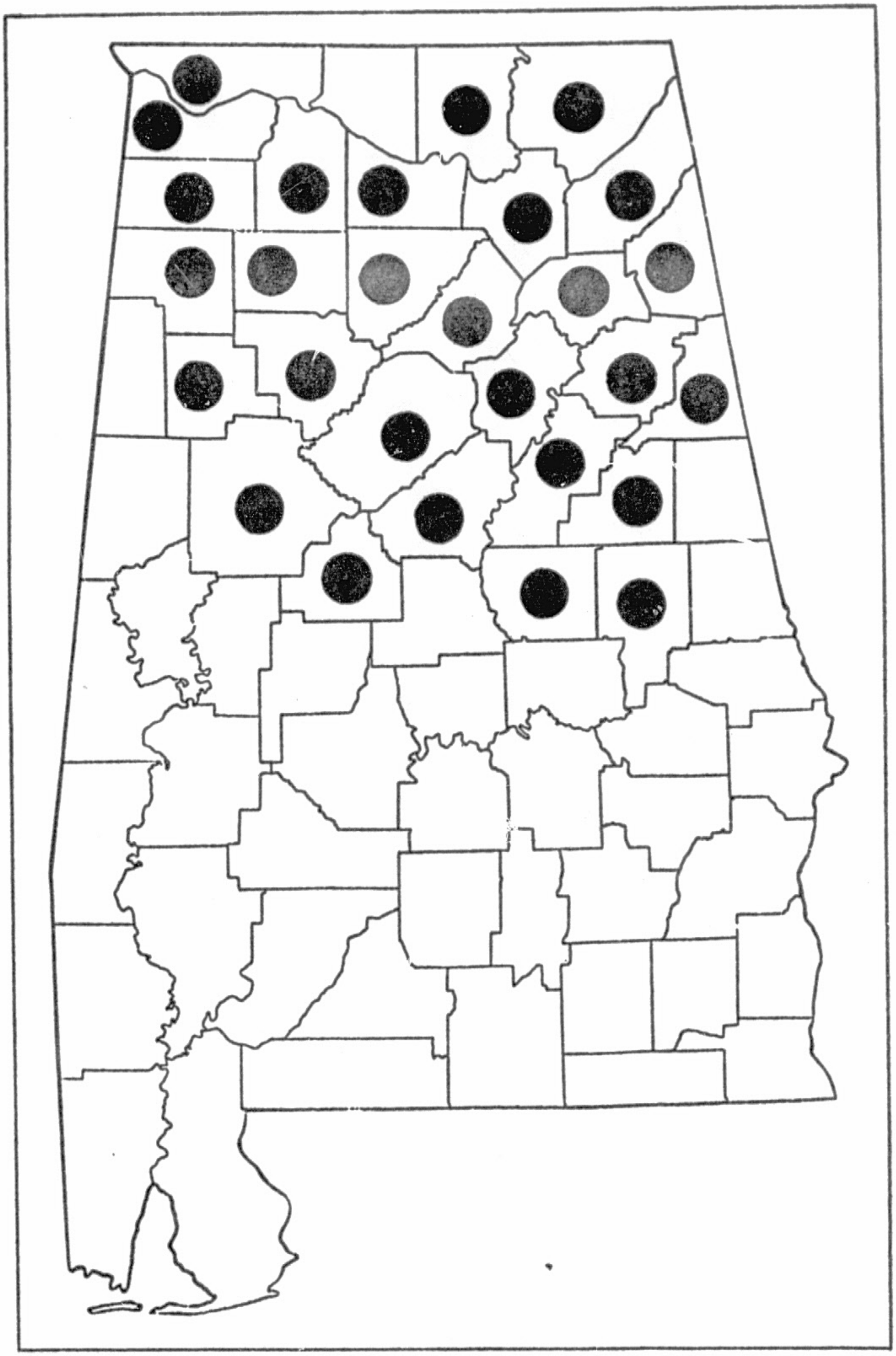

Figure 22. Range of Significant White Pine Presence in Alabama. Adapted from Ross C. Clark, The Woody Plants of Alabama (St. Louis, Missouri: Missouri Botanical Garden Press, 1972), p. 137

of one scene is included as a representative guide to further scene investigations. A location map of this image in relation to the State, as well as the other imagery available for study are depicted on Figure 23.

A false color added composite of MSS bands 4, 5, and 7 was chosen for detailed analysis because this photographic format presents a much sharper contrast among the various spectral signatures represwnted than do the black and white products (Figure 24). Therefore, identifying predominantly hardwood stands was greatly enhanced. The area for intense investigation was chosen to coincide with the predicted point of gypsy moth introduction into Alabama, image K-1 in the northeast corner of the State (Figure 25). This particular scene assumes evern greater benefit when noticing that it depicts various types of terrain representing three of Alabama's four physiographic provinces, the Appalachian Plateau (upper left), the Valley and Ridge (center) and the Piedmont (lower right).

The image was projected on a screen at an increased scale of 1:250,000 to better identify small isolated stands of hardwoods, then photo-reduced back to scale. From this projection a map delineating the predominately (greater than 50 percent) hardwood stands was produced (Figure 26). The basic criteria used in differentiating these forests from surrounding territory was a particular spectral, verified by ground truth and lower altitude imagery. It is widely known that within the Valley and Ridge Province of northeast Alabama hardwoods (mainly oaks) dominate higher elevations while mostly conifers (especially cedars and loblolly and shortleaf pines) can be found in the more acidic limestone valleys. At this point the assumption was made that the spectral signature assigned to these highland areas (especially in the north central

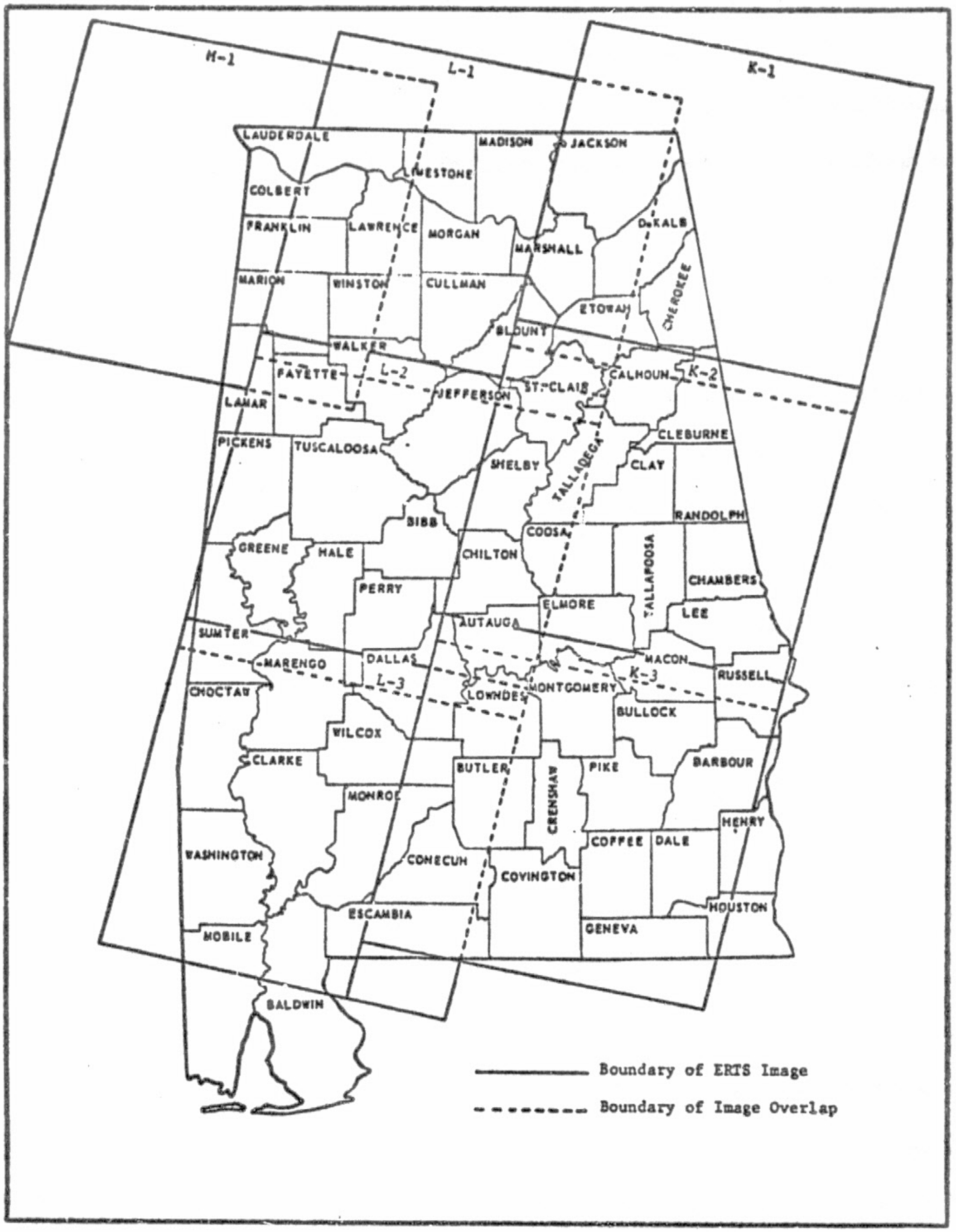

Figure 23. Location of ERTS Images Used in Delineating Alabama Forests Susceptible to Gypsy Moth Attack.

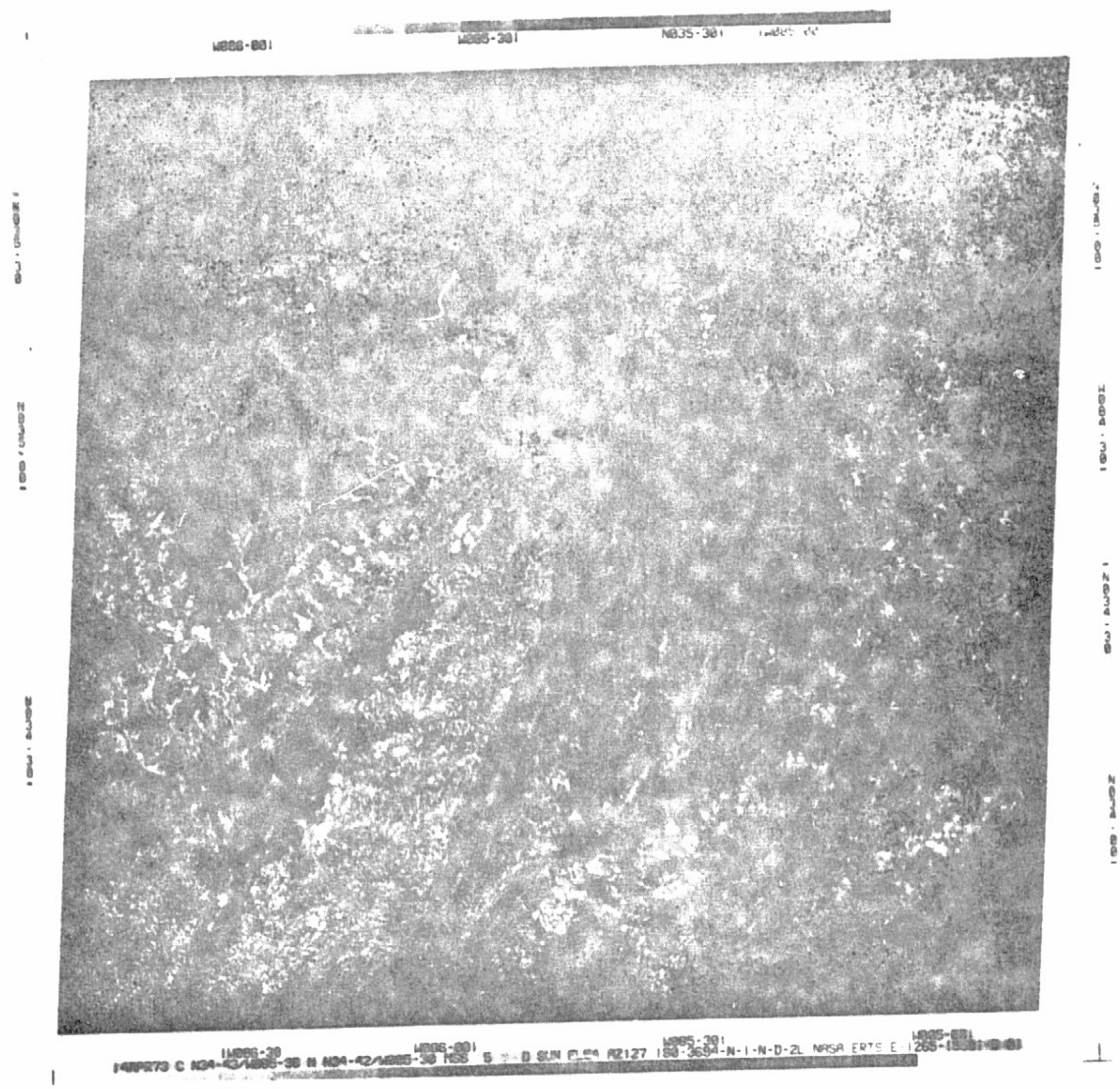

Figure 24. Black and White Image (MSS-Band 5) of Scene K-1.

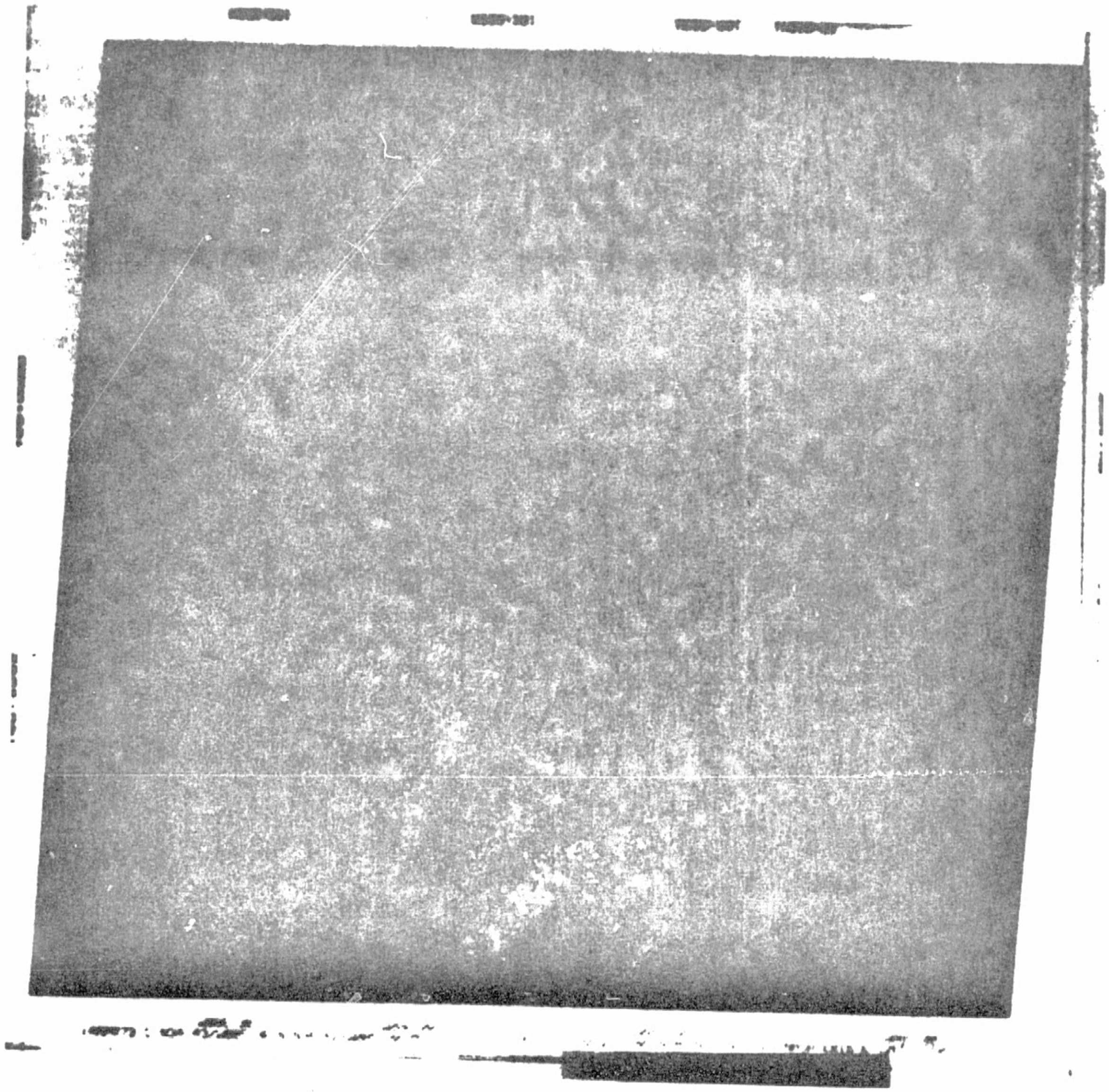

Figure 25. Color Composite Image (MSS-Bands 4, 5 and 7) of Scene K-1.

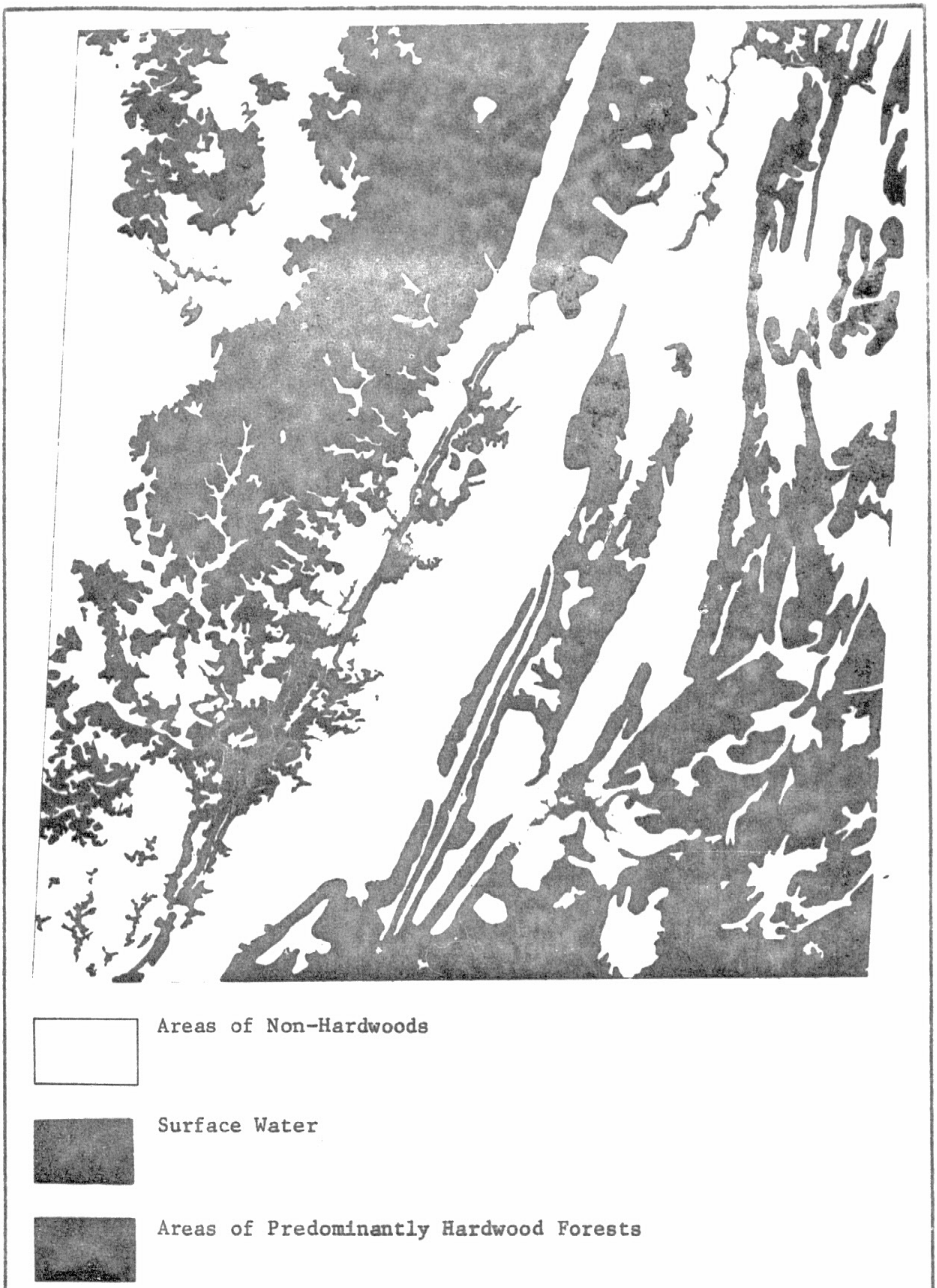

Figure 26. Hardwood Forest Map from ERTS Image of Scene K-1.

quatrant of Figure 25, page 99) could be applied to other areas on the same image for the identification of hardwood forests. The appropriate color in this case appears as a greenish-brown.

However, as seasons change so do the reflectance values of the same surface features. This factor, combined with variances in the development of original ERTS produce, in the possible image reproduction, in the choice of false colors to be added and in the amount of light intensity used in producing the color composites make it impossible to generalize the use of a particular spectral signature on more than one image. For instance, a visual survey of the images displayed in Figures 27-32 of appendix A illustrates the changes in the false color additives, as well as assigned light intensities. For example, scenes L-1, K-2, and L-2 possess a very similar signature for the same hardwood forests while these forests are depicted by a deep red color on scenes M-1, K-3, and L-3. These inconsistencies would indicate the need for a more constant control on color production before future analyses are attempted or ground truth for each image. And with the anticipated arrival of the gypsy moth being so imminent, it would seem that such needed quality photographic products would be a must (especially to satisfy various special interests) for a detailed survey of susceptible areas in Alabama to be accomplished.

Potential Effects of Expected Invasion

The serious magnitude of an anticipated invasion by an insect pest can often be measured best by impacts on other areas. For instance, the loss of oaks in a recreational or residential area could be catastrophic, as in New Jersey for example, the cost of wooded property is

about \$3000 per acre. In addition, the cost of removing a tree is from \$50-\$500, depending on size and accessibility, and with an average of about \$200. The average cost of replacing a three inch hardwood is about \$125 (including cost of plant, planting, one year's maintenance and guarantee) while the replacement of an eight to ten foot Austrian pine costs about \$80.[7]

Past observations have evidenced that the order of hardwood susceptibility to mortality from defoliation are: 1) white oak, 2) chestnut oak, 3) gray birch, 4) the red oak group (black, northern red and scarlet oaks), 5) red maple, 6) other birches, and 7) hickories. Hemlock can suffer heavy mortality from a single severe defoliation as does the young white pine. A 1972 study showed two consecutive heavy defoliations resulted in tree losses averaging 58 percent for white oak, 55 percent for gray birch, 46 percent for black and scarlet oaks, 27 percent for red oak and 26 percent for red maple. Mortality rates for all species tended to be highest among suppressed trees and lowest among dominant trees, reflecting health and vigor.[8] Since all these tree types are present to a great extent in Alabama (Figures 16-22, pages 89-95) and since all of Alabama's forests are at least the more susceptible (to attack) second growth, the impact of the impending invasion could be quite severe.

The loss of trees does not constitute the only adverse effect on forests by the gypsy moth. An additional consequence is the change in forest stand composition: 1) the accelerated decline of pioneer birch stands, 2) the reduced ratio of white oak to red oak, 3) an increase of the white pine component in mixed stands, 4) the influence on forest succession by hastening the death of short-lived, weak trees

and otherwise reducing the proportion of favored food, as well as the creating of conditions highly favorable to future epidemics, and 4) the slowing of radial growth of trees.[9]

During instars I through III, larvae feed mainly in the morning hours and only with temperatures above 45 °F. Therefore, the theory that destructiveness would be greatly accelerated in the warmer Southern forests seems to be substantiated. Also, the older larvae remain somewhat dormant during the daylight hours and begin to feed on the foliage in the evening except in high density areas where competition for food stimulates much more constant activity. During this period of darkness, larvae are less exposed to parasites and predators dependent on daylight vision, as well as important avoidance of high temperatures.[10] Thus, the gypsy moth's adaptiveness to a new environment, especially in the South, where summer nights are longer than in the Northeast (causing increased activity of older larvae) seems very much assured.

Other facets of the Southern environment must be considered when evaluating potentially ruinous consequences of insect infestation. For instance, in the case of organically polluted streams (only exceptions being mountain streams) by the gypsy moth larvae, the sudden removal of shade from the water can have deleterious effects on aquatic wildlife. The increased sunlight can cause an algae bloom resulting in the eventual death of some algae from overpopulation and subsequent food competition causing increased bacteria populations which in turn forces the dissolved oxygen to decrease to such a point that fish kills may be imminent.[11] This potential phenomenon is in addition to the obvious polluting effect of tons of larval excrement being washed into urban water

supplies.

In review, it would now seem that no realistic limits to gypsy moth population expansion now exist or can be expected in the foreseeable future. As a matter of fact, the only effective altering agents of the indicated trend are factors of acceleration: 1) an increased expanse of preferred host trees, 2) an increased inaccessibility of the forested areas (due to topographic irregularities), and 3) an increase in temperature within the proposed corridor of migration. With such factors present and with the susceptibility of southern forests accepted as a realistic assumption, the probability of an inevitible invasion (even before the predicted arrival date of 2011) in Alabama would seem quite high.

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(CHAPTER VI)

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[3]Ibid., p. 66

[4]Whiteford L. Baker, Eastern Forest Insects, Miscellaneous Publication #1175 (Washington: U. S. Department of Agriculture Forest Service, February, 1972), p. 323.

[5]U. S. Department of Agriculture Forest Service-Southeastern Area, State and Private Forestry Environmental Protection and Improvement, The Gypsy Moth-A Threat to Southern Forests (Washington: Government Printing Office, 1971), p. 11.

[6]Ibid., p. 9.

[7]U. S. Forest Service and Animal and Plant Health Inspection Service, op. cit., pp. 35 and 41.

[8]Ibid., pp. 8-10

[9]Ibid., p. 11.

[10]D. E. Leonard, "Feeding Rhythm in Larvae of the Gypsy Moth," Journal of Economic Entomology, Vol. 63 (October, 1970), p. 1454.

[11]George P. Whittle, personal interview, University of Alabama, April 13, 1973.

CHAPTER VII

SUMMARY AND CONCLUSIONS

In the preceding sections the basic factors of population dynamics which have enabled the gypsy moth to grow in statue from the relative obscurity of a Medford, Massachusetts, biological laboratory to a genuine natural threat in only 104 years have been enumerated and analyzed as to their relavancy. The net effect of each element has been correlated with historic data to achieve a possible cause-effect relationship to future growth patterns. In addition, a review of the gypsy moth's record as an environmental disruptor and as a living economic adversity has been offered in light of anticipated future impacts. Other historic data were compiled and analyzed to determine not only if the present population expansion rate will continue but also the approximate date of the expected invasion of Alabama. This chapter will include both a summary of these investigations as well as the proper conclusions which can be derived from them.

The Gypsy Moth: A Real Threat?

Whether or not the actual target date for introduction of the gypsy moth into Alabama of 2011 is accepted, the contention that a threat does exist for some time in the forseeable future must possess a great deal of merit. A mere glance at the map of past spread (Figure 2, page 23) would offer a strong indication the moth populace is definitely on the move.

Even greater concern than that for any dire statistical projections made in this study should be prompted by an in-depth survey of the major control forces (or the lack thereof). Other than the broad expanse of unforested territory of the Great Plains, absolutely no permanent land barrier to population diffusion exists. Furthermore, it is conceivable that even the present limiting factors of the pine-forested Coastal Plain and the conifer expanse of the Canadian taiga (with its currently fatal low temperatures) could conceivably change as the insect continues its characteristic evolutionary adaptability.

But on a more contempary basis, every attempted deterrent to population growth seems of either negative or neutral effectiveness. The larvae have progressed through the air in a westerly and southwesterly direction in spite of the seemingly prevailing headwinds. Patterns of precipitation which have a sedating effect on en mass migration activities do not seem to vary within the potential territorial expansion. Also, in the laboratory a remarkable ability of the moth to accelerate maturation time when subjected to cold temperatures has demonstrated the possibility for survival in an even colder climate than was previously expected. In short, the gypsy moth has moved through an ever-changing exotic environment without any signs of faltering. In addition, the only accepted probability for alteration of morphology due to climatic conditions would be an acceleration resulting from the development of multiple generations per year (because of warmer temperatures) as the southerly migration continues.

Furthermore, the virtual handcuffing of government agencies in their battle with the moth by the ban (blanket spray) of DDT has almost

assured the insect of survival. By their own admission, Department of Agriculture officials have adopted a policy of controlling localized outbreaks while apparently being resigned to defeat in their efforts to halt natural spread. This lack of combative facilities, as illustrated in both Table III, page 34 (summary of defoliation) and Figure 14, page 85 (areal expansion) as population build-up and destructiveness remained static throughout the 1930's and 1940's and even decreased dramatically in the 1950's due almost exclusively to the use of DDT. In the same graphics, a sudden boom of activity can be seen in the 1960's through the present. During this period, the government has continued a program of attempted control with inferior weapons, as most currently used methods of suppression do not even hold the pest in check. However, in fairness to government officials, they are charged with guarding our natural environment, and every conceivable effective suppression tool has displayed adverse effects on the local ecology. And so, continued assault on our forest resources by the gypsy moth goes on unimpeded.

As was previously mentioned, no place in the eastern half of the United States is immune to the potential impact of this forest pest. Approximately 75 percent of this section of the country is covered by suitable host forests, so the losses could be catastrophic.

Needed Preparation?

Since it now seems that there exists no convential means of halting the gypsy moth's territorial expansion, the logic of merely accepting the inevitibility of the onslought and beginning preparation on a local basis is very much warranted. In any battle, the best means of

enhancing one's odds is by increasing friendly numbers. Therefore, the most sensible approach to the problem is to make full use of the potentially useful tool, education.

In the past monitoring techniques such as the reported findings of park rangers, a running estimate of defoliated areas and survey campaigns using sex lure-baited traps have met with little success. Even the use of remotely sensed data, as was proposed in this study to detect infested areas has failed. The investigation of color composite ERTS imagery from known infested territory did not reveal any unique spectral signatures attributable to gypsy moth (Figure 27 of Appendix A), probably due to the green undergrowth present in most hardwood forests, creating a similar reflectance value even after the canopy of foliage has been stripped.

It is, therefore, strongly suggested that two related programs be implemented: 1) the mapping of the most susceptible (to infestation) target areas along avenues of future geographic diffusion in order to be prepared to most efficiently utilize the limited suppression tools available, and 2) the effecting of a massive interstate campaign to make the public aware of the inevitable threat. After all, no better survey team can be found than a highly mobile populace with the ability to spot a gypsy moth in any stage of development. Furthermore, no governmental program can work to any acceptable degree without public support and tolerance of the probable adverse side effects associated with any insect control activity. And a stepped-up research and development program remains the only answer to the ever-growing gypsy moth problem. The pest must be located along fringe areas still in the initial phase (isolated and spotty infestations) of population growth when it

can be eradicated by toxic insecticides without harming the ecology of a very large area. Also, new suppression tools which can offer protection from gypsy moth destruction while inflicting minimal damage on the environment will have to be developed, all of which is very costly. It is with these points in mind that the public must be made a part of the battle against the gypsy moth.

APPENDIXES

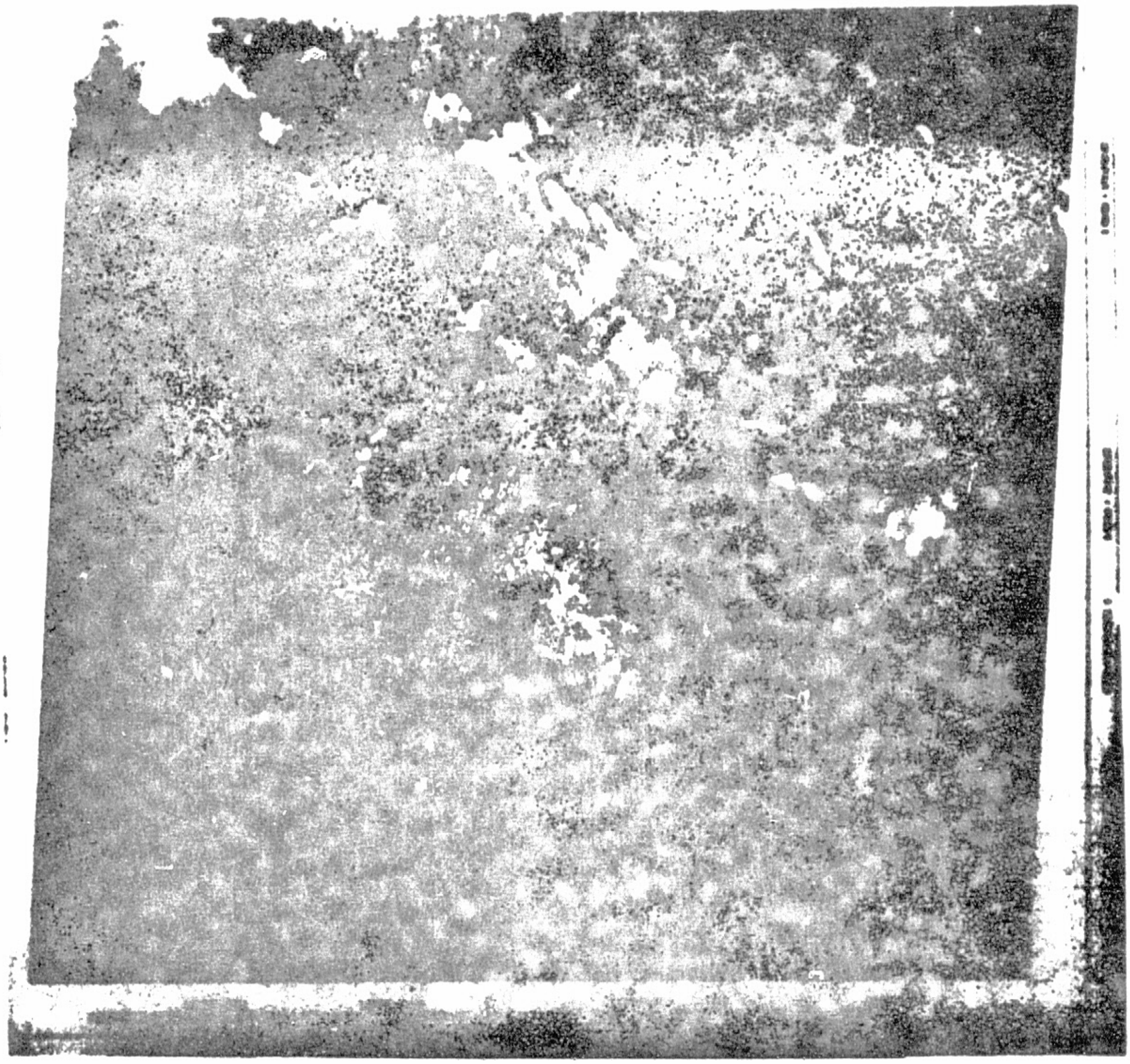

Figure 27. Color Composite Image (MSS-Bands 4, 5 and 7) of Scene L-1.

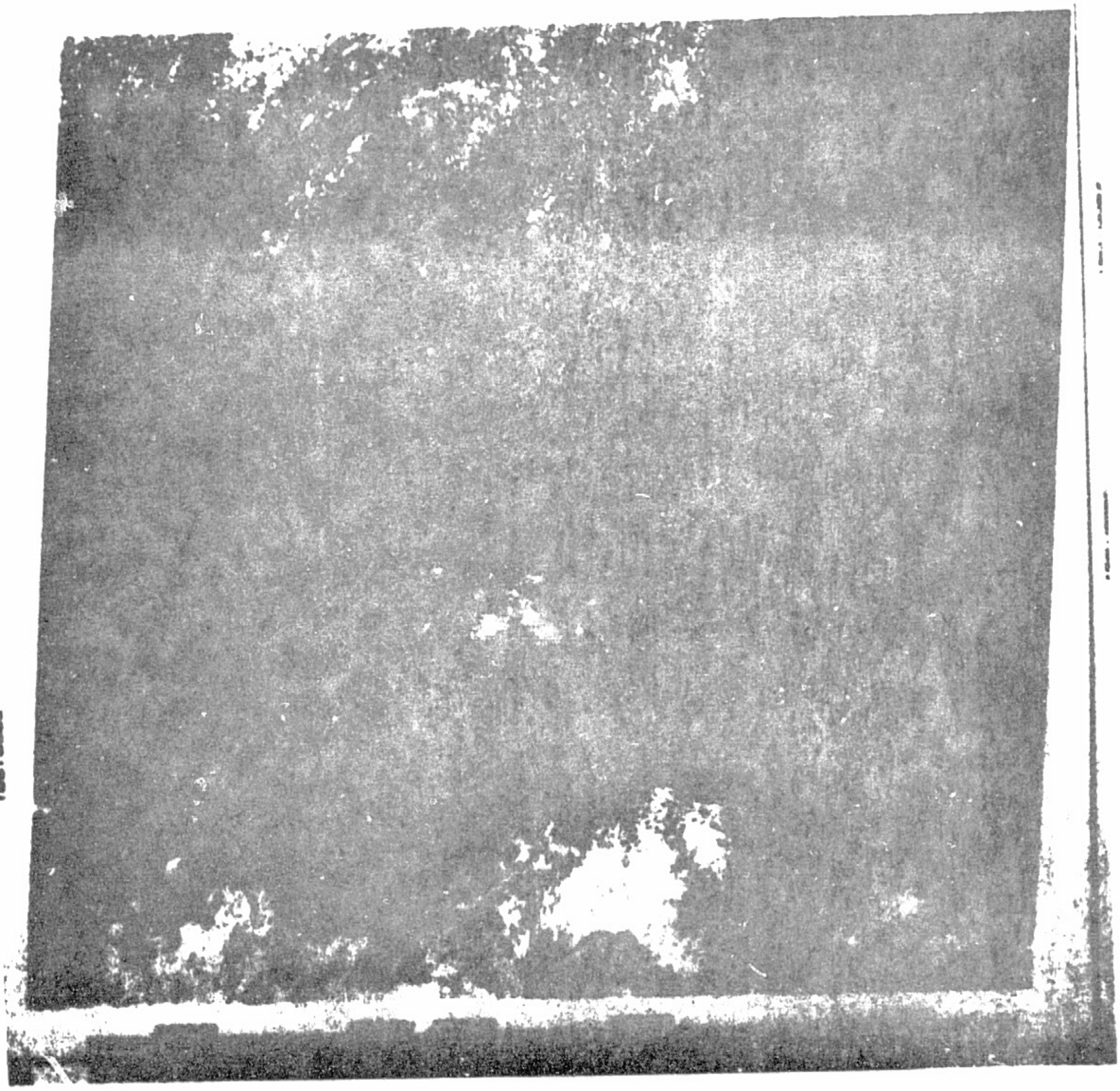

Figure 28. Color Composite Image (MSS-Bands 4, 5 and 7) of Scene K-2.

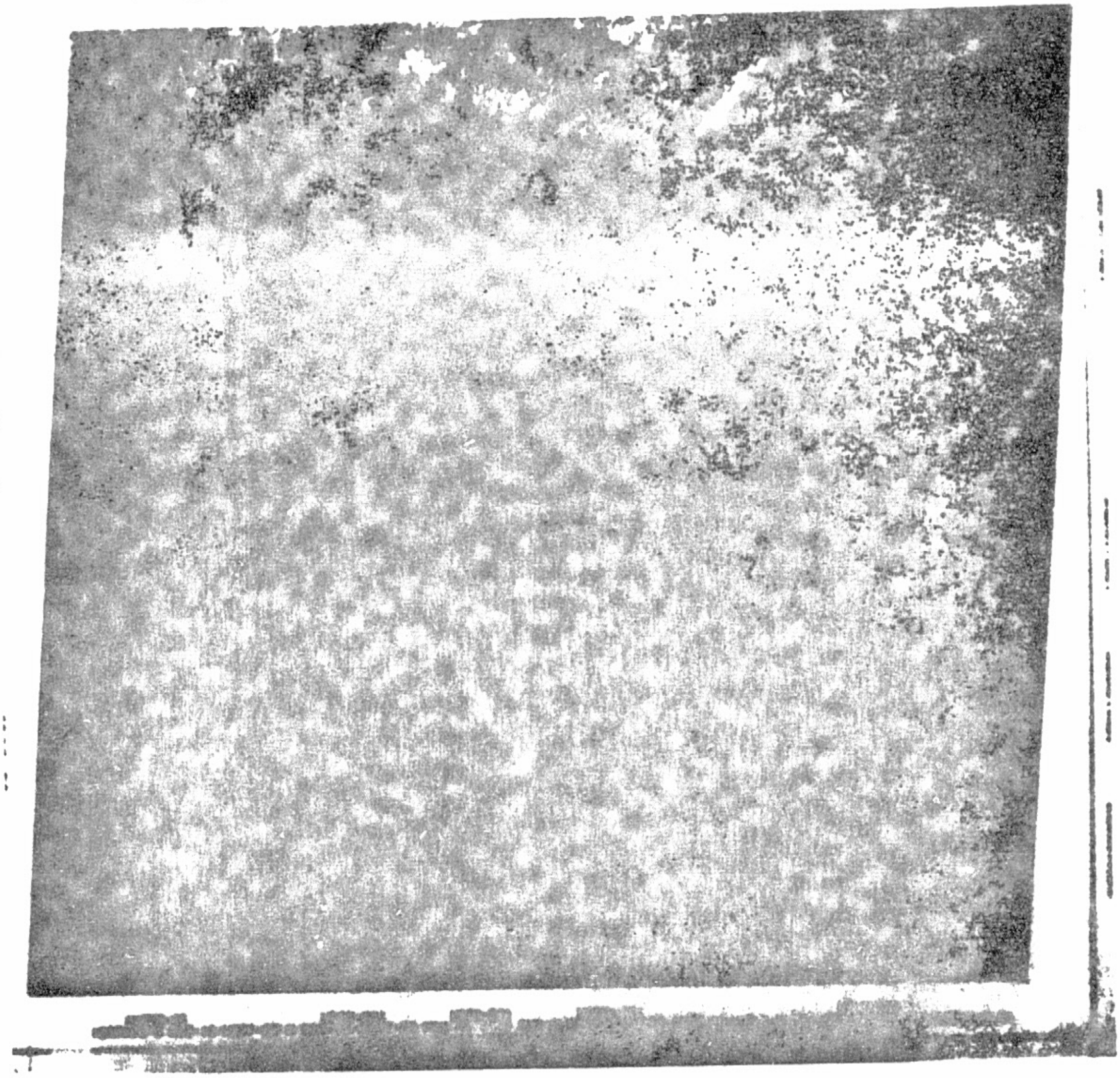

Figure 29. Color Composite Image (MSS-Bands 4, 5 and 7) of Scene L-2.

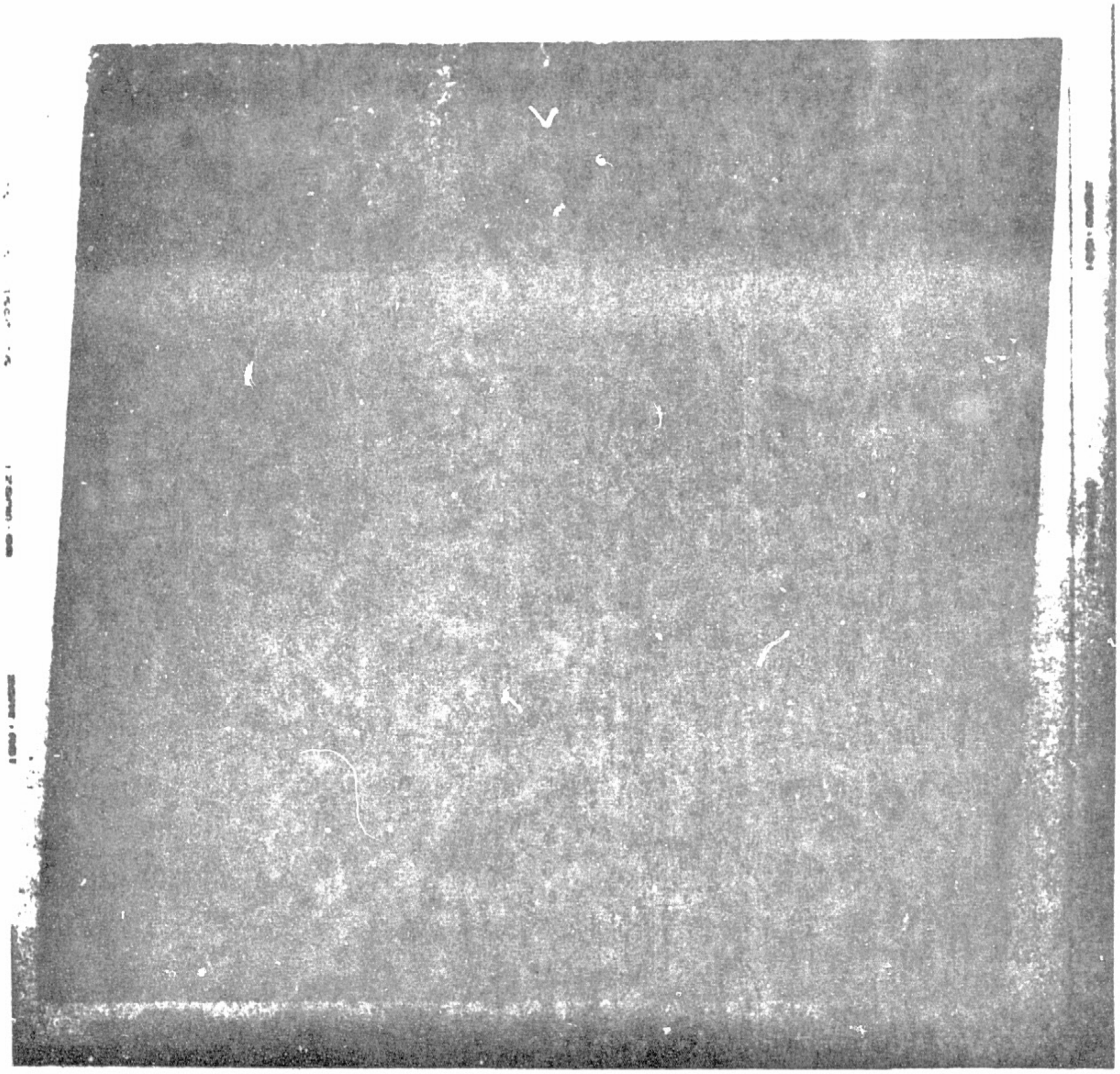

Figure 30. Color Composite Image (MSS-Bands 4, 5 and 7) of Scene M-1.

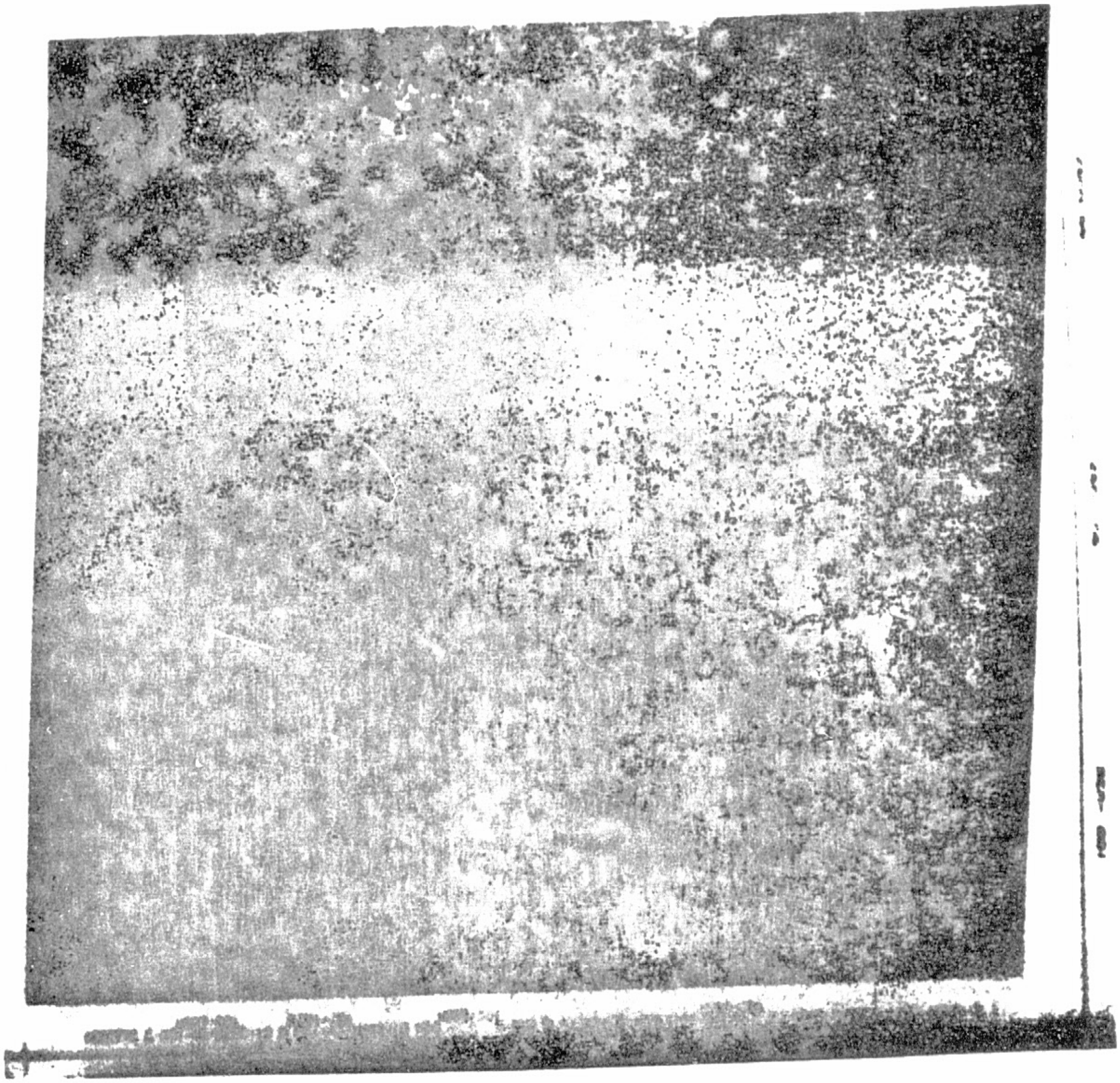

Figure 31. Color Composite Image (MSS-Bands 4, 5 and 7) of Scene K-3.

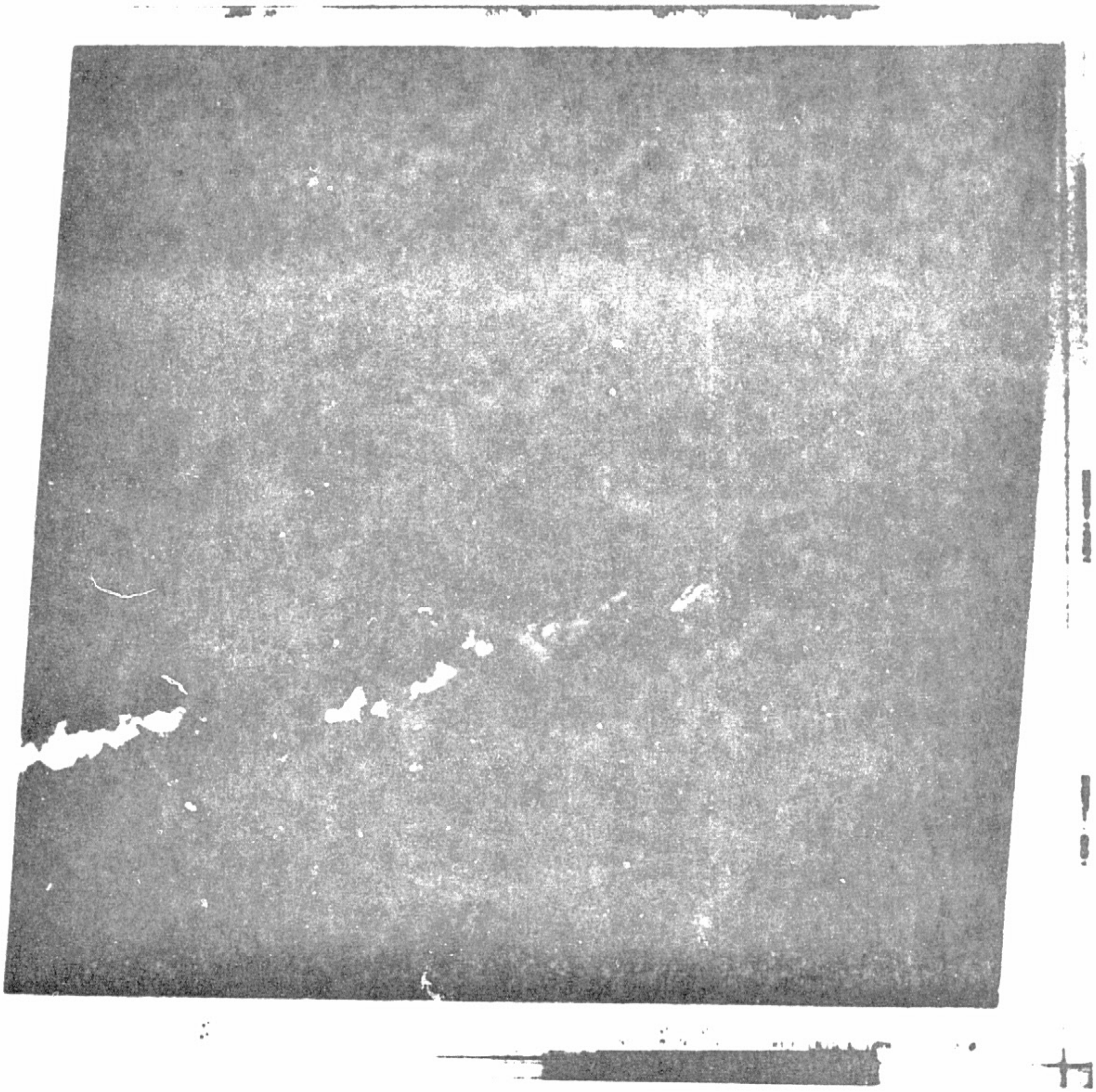

Figure 32. Color Composite Image (MSS-Bands 4, 5 and 7) of Scene L-3.

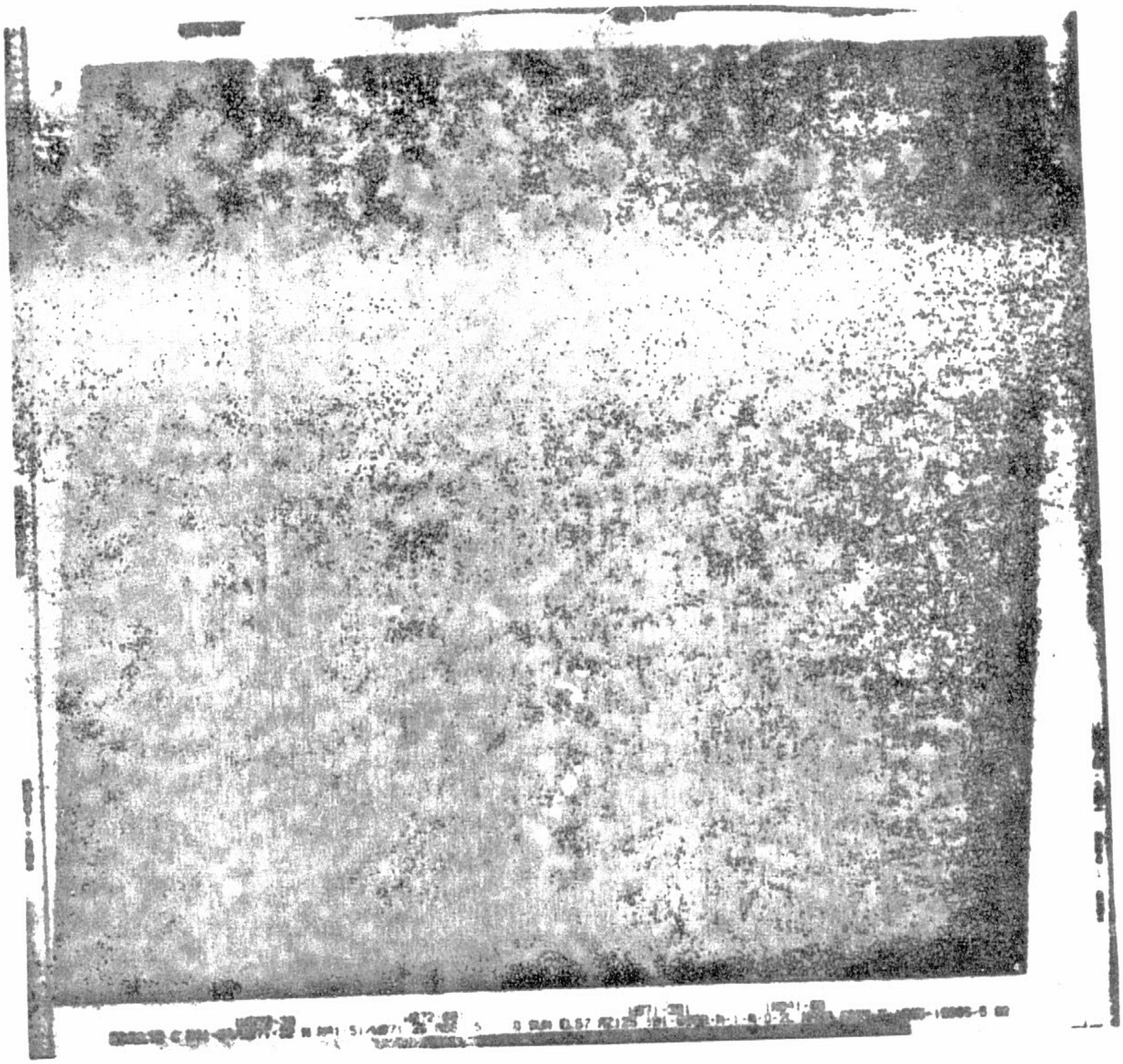

Figure 33. Color Composite Image (MSS-Bands 4, 5 and 7) of the Massachusetts Scene.

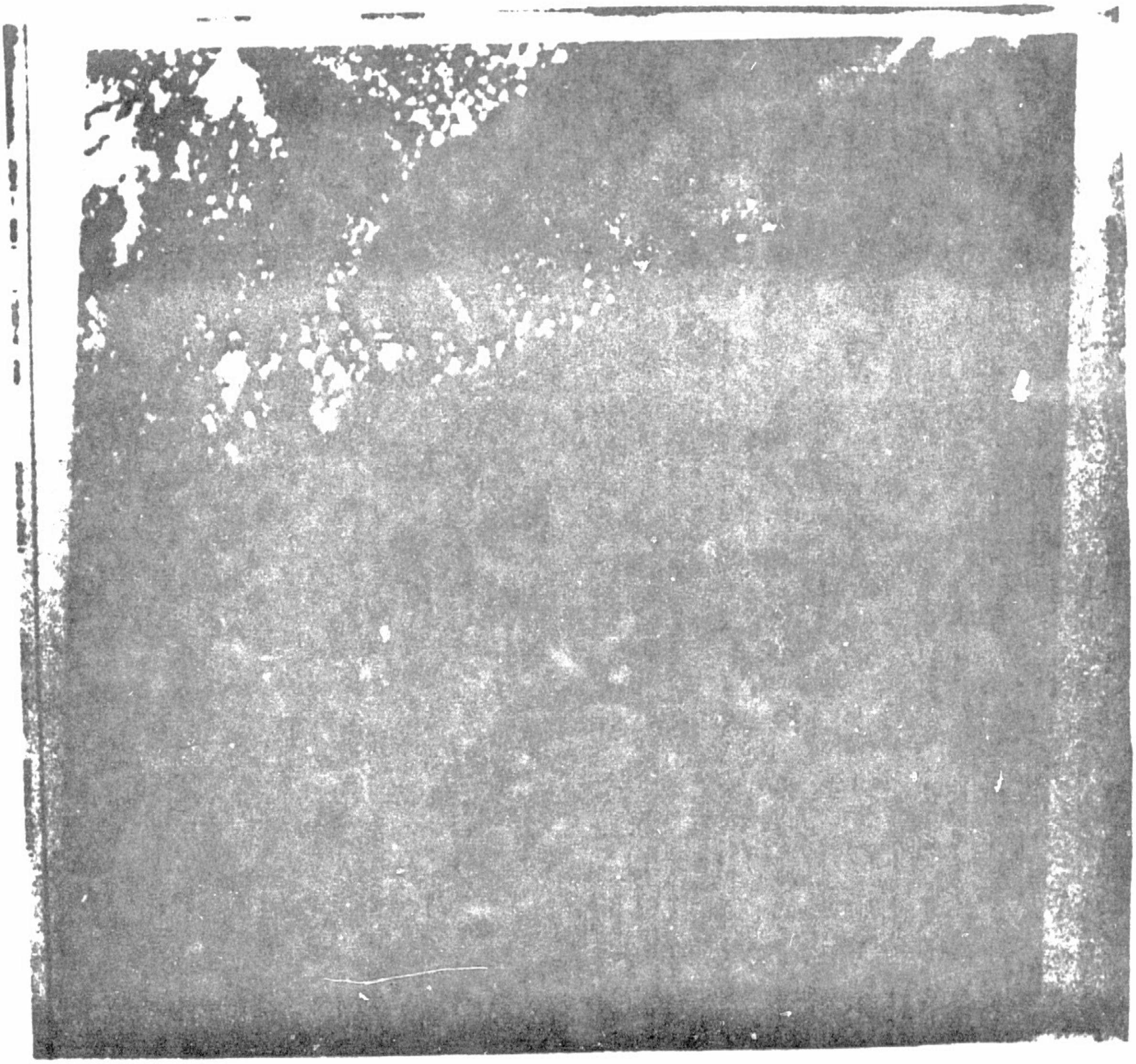

Figure 34. Color Composite Image (MSS-Bands 4, 5 and 7) of the Long Island Scene.

APPENDIX B

EXPLANATION OF REGRESSION ANALYSIS

The existence of some relationship between the historic arial spread and time was assumed. After various investigations as to what operations best described this relation, several functions were picked as the most likely ones to depict this relationship. These functions were then implemented in an attempt to predict future spread. Some of the functions were clearly unacceptable to project the future trend; for example, two of the trend functions caused decrease at some point in the future while it is evidently clear from review of historic data that the function of area must increase with time.

The most stable function and the one having the least error between time observed and time calculated by formula was:
$Y = 16.8616 \cdot 1 \log_{10}(X) + .00008289 \cdot X$ whereas Y = time and X = area.
The ultimate prediction of gypsy moth spread to the point of introduction into Alabama was made on the basis of the above operation.

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THE APPLICATION OF THE COMPOSITE SEQUENTIAL CLUSTERING TECHNIQUE TO ERTS DATA OF SELECTED STUDY AREAS IN TUSCALOOSA COUNTY, ALABAMA

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SECTION NINE

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VOLUME TWO

INVESTIGATIONS USING DATA IN

ALABAMA FROM ERTS-A

THE APPLICATION OF THE COMPOSITE SEQUENTIAL CLUSTERING TECHNIQUE TO ERTS DATA OF SELECTED STUDY AREAS IN TUSCALOOSA COUNTY, ALABAMA

by

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LIST OF ACRONYMS

ASCS	Agriculture Stabilization and Conservation Service
CCT	Computer Compatible Tape
CSC	Composite Sequential Clustering
DCP	Data Collection Platform
ERTS	Earth Resources Technology Satellite
GKMC	Generalized K-Means Clustering
MSS	Multispectral Scanner
NDPF	National Aeronautics and Space Administration Data Processing Facility
RBV	Return Beam Vidicon
SSC	Statistical Sequential Clustering
UTM	Universal Transverse Mercator (map coordinates)
WBVTR	Wide Band Video Tape Recorder

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CHAPTER I

INTRODUCTION

1.1 The Need for Land-Use Data

One of the most important challenges of the future is monitoring man's effect on the land. The amount of land is finite while the demands on the land are increasing. Each year the earth must support more people. Since any condition approaching zero population growth cannot be expected for many years, if ever, the demand on the land cannot be expected to stabilize. In the United States there is also a trend toward smaller families, increasing the demand for land area to accomodate more households per unit of population. In addition, families have higher average incomes enabling them to travel more and consume more.

These developments result in the often unsightly spread of housing developments, factories, and the accompanying service facilities required. Precious open space, productive agricultural land, dense forest, and scenic coastlines have been exploited in many cases. Too often this condition has resulted from poor planning. A more organized approach is required involving systematic land-use planning, whereby the government exercises its right to eminent domain to direct and control land utilization.

Until recently the problem of land-use planning has been largely unaddressed. The need to clean up dirty water, polluted air, and our accumulated solid waste seemed more pressing. Several recent developments, however, point up the growing awareness of the need for land-use planning.

The National Land Use Policy and Assistance Act is being considered in Congress. This legislation proposes that each state inventory its land and develop a state-wide land-use and regulatory plan. A typical plan would earmark specific land for large-scale development, environmental preservation, and public facilities. States that did not comply would face having their share of federal funds reduced.

In a separate development, a task force appointed by President Nixon submitted a report recommending a wide assortment of measures for more rational land use. The report appears to have been written to placate the conservationists.[1] In one of its major conclusions it states, "It is important that state and local legislative bodies continue to adopt planning and regulatory legislation aimed at carrying out land-use objectives and that legislative bodies make clear that police powers are regarded as valid authority to achieve more orderly development and to protect natural, cultural, and aesthetic values."[2]

In view of the current interest in land-use planning, the availability of timely land-use data is especially important. Consequently, the development of techniques to gather and interpret the needed land-use data takes on added significance.

1.2 Objective

Gathering land-use data from remotely situated vehicles (remote sensing) is a particularly promising approach to compiling up-to-date land-use inventories. A variety of sensors have been developed to gather data and a number of techniques devised to interpret it. A discussion of the types of sensors and the interpretation methods is presented in Chapter II.

One of the most significant developments in remote sensing technology is the Earth Resources Technology Satellite (ERTS). Since the sensors are aboard a satellite instead of an aircraft, land-use data can be gathered repetitively on a global scale.

Under the National Aeronautics and Space Administration research contract entitled "Investigations Using Data in Alabama From ERTS-A", investigators at The University of Alabama have undertaken the task of interpreting ERTS data for the State of Alabama. This task involves developing and testing interpretation techniques in order to determine how they apply to the specific ERTS data for the state, with the ultimate objective of providing interpreted data in such a form amenable to use by policy makers and regulatory agencies.[3]

One interpretation technique that is available to the ERTS effort is the composite sequential clustering (CSC) technique. It is an unsupervised classification technique which automatically groups the land into a number of categories according to the ditital data collected by ERTS for each section of land. The technique's final product is a digital map of an area with the locations of each category

delineated. If the CSC technique is to be useful in the inventory of land use from ERTS data of Alabama, several things must be investigated. Specifically, the exact relationship between the automatically derived categories and interpreted land-use categories must be understood. This understanding can only be gained by applying the technique to areas in a variety of regions throughout the State, during different seasons, and under varying conditions. Only then can the technique's utility as a tool for deriving timely land-use data be ascertained.

At this point, the CSC technique has been applied to only one area in Alabama. An area including the Huntsville Alabama Jetport was studied by Mr. Robert Cummings of the Marshall Space Flight Center. To provide a more comprehensive understanding of the techniques utility, additional study areas must be analyzed in other regions.[4]

This study was designed to satisfy part of this need by analyzing areas selected from the region around Tuscaloosa, Alabama. The ERTS data used for analysis was gathered during early spring (March 28, 1973). The Tuscaloosa area was chosen for several reasons. One of the reasons for selecting this area was the great diversity of land use existing within a small area. Consequently, the study areas can be relatively small. Ample ground-truth data is available in the form of multispectral photographs taken during U-2 underflights on February 22, 1973, and RB-57 underflights on April 29, 1973. Low-altitude coverage (12,600 feet) of the Tuscaloosa area was flown May 18, 1973. Another advantage of selecting study areas near Tuscaloosa is the close proximity to The University of Alabama. This facilitated the

gathering and checking of ground-truth. Spring coverage was chosen because the high altitude underflights used for ground-truth were available only for this season.

1.3 Scope

The composite sequential clustering technique employs the data from the satellite to ascertain the number of land uses that can be discerned and to print out the location of the various classes of land use. The primary question to be answered when applying the technique to an area is how many different types of land-use classes can be discerned while still maintaining an acceptable degree of accuracy. The main thrust of this investigation is then to determine what types of land use are easily identified by the unsupervised interpretation of ERTS data (indicated by high classification accuracy) and what types of land use cannot be easily identified (indicated by low classification accuracy).

The land within each study area is assigned to a land-use class by its ground cover. Hence, in a sense, the term "land-use class" is misleading. The area is not necessarily classified as to its use but rather as to its ground cover. It is the characteristics of the area's cover that is sensed by ERTS and used to classify the land. Anderson et. al. (1972) concludes that land cover is the basis of categorization of land use at the primary level.[5] Therefore, for our purposes, the area's land cover is the only criterion for land use. Despite its inaccurate connotation, the term "land use" will be used interchangably with the terms "land cover" and "ground cover".

Each data point from ERTS represents a "composite" of land-use information for an area 70 kilometers (230 feet) square. An area this large can easily contain more than a single type of land cover. For example, a data point might contain a building, a wooded area, and a section of road. The combination of reflectance may make such a point unclassifiable. In any case, such situations are analyzed.

The land-use classification system used in this study is arbitrarily contrived to meet the needs of the areas studied. Typically the user and the situation dictate the classification system that is used.[5] Although a classification system specifically for remotely sensed data has been devised by Anderson, no attempt is intentionally made to relate land use in the Tuscaloosa area to it. Whether the resulting land-use classes conform to any classification is secondary. The primary criterion is rather that they can be effectively identified from ERTS data by the unsupervised classification technique.

The unsupervised clustering technique used in this investigation is one of many such techniques. Although some of the various techniques are discussed, no attempt is made to evaluate the merits of the CSC technique relative to other methods on the basis of their performance in the study areas, whether it be in terms of the speed or accuracy of classification.

As outlined in the previous section, the study areas used for analysis should contain the types of land use that are characteristic of the region. This implies that some region be defined in West Alabama, and study areas selected such that every type of land cover is represented. A

comprehensive study of this sort is not within the scope of this study. A quick examination of the air photo coverage of the Tuscaloosa area, however, revealed the major types of ground cover that were present and should be included in the study areas.

1.4 Procedure

1.4.1 Selection of Study Areas

The initial task was to establish criteria for the selection of the study areas. These criteria (section 6.1) were selected in such a way that many factors affecting the quality of the ERTS data and the effectiveness of the clustering technique could be studied.

With these criteria in mind, study areas were chosen by examining high altitude photography of the Tuscaloosa area (February 22, 1973 coverage). Several areas meeting the criteria were delimited on a transparent acetate overlay. These areas were then reduced in area as much as possible while still maintaining their usefulness. After the exact location of the areas had been decided, they were located on maps according to the Universal Transverse Mercator (UTM) coordinate system which is the standard system by which all land-use information in the ERTS project is located. Finally those study areas of less importance were discarded.

1.4.2 Selection of ERTS Data

ERTS data of the area from early 1973 was examined to find the most suitable data for analysis. Its suitability was judged from the amount of cloud cover, the quality of the data, and the date it was collected.

The March 28, 1973 coverage was chosen (ERTS frame E-1248-15562). Although some clouds were over portions of Tuscaloosa County, the areas of interest were largely cloud free. The quality of the data was excellent and was gathered within five weeks of the February air photo coverage.

The actual processing of the digital data was done by personnel at the George C. Marshall Space Flight Center. To initiate this action, a data processing request form was completed for each study area. To complete this form, each study area was first located within the ERTS data (section 3.4). To complete the necessary information, the number of land-use classes desired from the classification in each study area and the number of spectral bands used to image the area were listed.

1.4.3 Gathering of Ground-Truth Data

Prior to completion of the automatic classification, information was gathered concerning the ground cover of the study areas. This information, commonly called ground-truth, came from several sources.

The primary source was high altitude photographs. An air photo of each study area was selected and this served as the base for the ground-cover or ground-truth map. The air photo was first projected to a workable scale. From this projected image the area's ground cover boundaries were drawn on translucent mylar. This boundary map was then used for notations concerning various characteristics of the region's land cover and as the base for the area's ground-cover map.

The primary task in the production of a ground-cover map was identifying the region's ground cover in such a way that all land in the region could be classified into one of a finite number of categories. To do this, the information contained in air photos of each study area was supplemented by field checking, examination of low altitude imagery, and interviews with those familiar with the agriculture, forestry and mining of the area. This supplemental information aided in the interpretation of the air photo so that the area's land cover could be grouped into classes and a ground-cover map produced.

1.4.4 Analysis of the Unsupervised Classification

After the results of the clustering technique were received, the first task was to locate the digital data on the ground-truth map. This was done by overlaying the ground-cover map with a sheet of mylar and referencing various features that were recognizable on both the ground-cover map and the computer classification with their location in the digital data. These reference points throughout the study area were then used to size and fit a grid of data point locations over the entire area.

This grid was used two ways. In one application it was used to digitize the ground-truth map. In other words, the dominant category of ground cover for each data point or each cell in the grid was coded onto computer cards for subsequent automatic comparison with the computer classification. This automatic comparison simply noted how the

unsupervised classification of each data point compared with the classification on the ground-truth map, noting each combination of interpreted ground cover category versus automatically-derived category, and displaying the results in a matrix where the number of data points with each type of combination was shown. For example, a typical number in the matrix indicates how many data points interpreted as pine forest were classified by the clustering technique into one automatically derived category.

The grid was also very useful in visually comparing the two classifications. This was done by using the grid to produce a color coded digital map of the automatically classified categories. By simply overlaying both the digital map and the ground truth map, visual comparisons were possible. The digital map was also very helpful in detecting patterns in the classification.

Analysis of each study area involved evaluating the classification technique's effectiveness as a tool to inventory land use. There were several statistical and visual tools instrumental in making this evaluation. An adequate description of all these tools is not possible unless the reader has some understanding of the multispectral technique and the ERTS data. Consequently, the specific methods used to evaluate the unsupervised clustering technique will be discussed in Chapter VII when the results are presented.

CHAPTER II

THE MULTISPECTRAL TECHNIQUE

2.1 Principles of the Multispectral Technique

Multi-band spectral reconnaissance techniques are particularly useful in remote sensing. Colwell cited many uses of the technique as early as 1961.[6] These applications include detecting land use as well as such developments as the electron microscope, X-rays, thermal infrared photography, and remote sinsing of submerged land.

The characteristics of an area on the ground are obtained by recording the energy that the area either emits or reflects. Normally, for each type of ground cover, there is a unique way the reflected and emitted energy lemels (usually reflected sunlight) vary with the wavelength. Our eyes or a single sensor only detect a relatively narrow r range of wavelengths (Figure 1). If there is a large number of land-cover types in an area, there is a high probability that several types of land cover may have similar levels of reflected and emitted energy (or similar reflectance values) in the particular range of the sensor. Consequently, accurate identification of the land cover in each area would be difficult since each area would appear approximately the same tone.

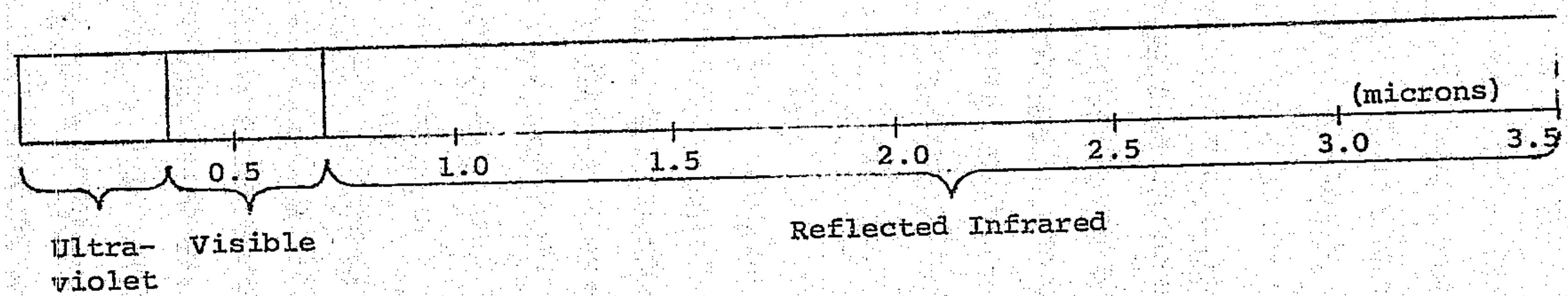

Figure 1. Electromagnetic Spectrum

In the multispectral technique, more than one sensor is used, each detecting reflectance in a different part of the electromagnetic spectrum. Although several types of land use may have similar reflectance values in one portion of the spectrum, they will not be the same in other portions of the spectrum. By interpreting the combinations of photographic tones or voltage readings from the sensors, land use can be accurately identified for very complex and diverse regions. In other words, several properly selected narrow-band sensing devices can be used in concert to more accurately determine land use than a single wide-band sensor.

2.2 Types of Multispectral Sensors

The types of sensors used in multi-band spectral reconnaissance can be divided into three major groups: multi-lens photographic systems, optical-mechanical scanners, and radar systems.

2.2.1 Multi-lens Photographic Systems

Multi-lens photographic systems are probably the most commonly used devices in gathering multi-band spectral data. An area is photographed simultaneously by several cameras or lens systems responding to many parts of the electromagnetic spectrum.

There are several important limitations involved in obtaining satisfactory images with this system and also with analysis of the data. Although there is considerable detail in a photographic process, there is relatively poor spectral

resolution. Photographic film emulsions have a relatively narrow spectral range of sensitivity. Other types of multi-band systems must be used for wavelengths shorter than about 0.35 microns and longer than about 0.95 microns.[7] Analysis usually involves superimposing the images and enhancing the spectral characteristics of each image with the additive color technique. Uniform geometric relationships from image to image are necessary if this is to be done. Consequently, the checking of lenses for accurately matched distortion, focal length, and alignment of their optical axes is necessary to insure uniform geometrical relationships. Since accurate camera calibration and carefully controlled film processing are essential for obtaining accurate results, such systems can be costly.

There are several limitations involved when computer analysis is applied to this type of data. For computer analysis the reflected energy must be given a quantitative value. The photographic materials in this process are simply chemical detectors of the reflected energy over a portion of the spectrum. The emulsion of the film is transformed by exposure to the light energy which produces increasing density after development. The reflectance is quantitized by measuring the film density with a densitometer. The densitometer scans the photographic transparencies. The transmitted light is measured and this is expressed in terms of density. This process degrades the spatial resolution. Consequently, a substantial amount of available information is lost. Other problems include the inability to achieve the exact point-by-point spatial congruence required for computer analysis because of such factors as variable film shrinkage and differences between lenses.

2.2.2 Radar Sensors

Radar sensors are unique in several ways. Whereas most sensors detect reflected solar radiation or emitted radiation or both, radar provides its own source of "illumination". A pulsed signal is emitted from the radar system and then it detects and records that portion of the signal which returns from terrain features below. Consequently, it can obtain the same information day or night. Imagery can also be obtained of regions obscured by clouds. Radar data is especially amenable to quantitative analysis since the nature of the illumination source is accurately known. On the other hand, the spatial resolution of this data is relatively poor and the equipment required is rather complex.

2.2.3 Optical-mechanical Scanner Systems

The detection of reflected electromagnetic energy beyond the visible and photographic infrared region requires a different type of sensor typified by optical-mechanical scanners. These devices disperse the reflected and emitted energy into specified relatively narrow band-widths with a prism spectrograph, and electronically record the percent reflected in each region. Consequently, each resolution element is simultaneously scanned in many spectral bands. The device scans a path perpendicular to its own relative motion by means of a rotating or oscillating mirror.

Although this system is limited by poor spatial resolution, its inability to penetrate clouds, and its complexity, it is particularly amenable to analog, digital, and hybrid computation. Also, the use of dispersive optics and electronic blocking techniques allows greater flexibility in the

choice of bandwidths in the electromagnetic spectrum than with standard film-filter combinations. Unlike multi-lens photographic systems, the imagery from all bands is completely synchronized in both time and space since it is all acquired through the same optical system. These capabilities give optical-mechanical scanner systems, such as the multispectral scanner on ERTS, a tremendous potential for remote sensing.

Its application to land-use inventorying is especially promising. As cited by Colwell, a thorough spectral definition of an area is necessary for accurate classification.[6] Consequently, the optical-mechanical scanner is uniquely amenable to the task of gathering land-use data because of the wide range of reflectance that can be measured.

CHAPTER III

ERTS AND REMOTE SENSING

3.1 Significance of ERTS

The ERTS system represents a significant merging of space and remote sensing technologies for collecting multispectral images of the earth and collecting environmental data from earth-based instrument platforms. The ERTS program is primarily a research and development system. Its purpose is to demonstrate that remote sensing from space is a feasible and practical approach to efficient management of the earth's resources. It is hoped that the data acquired and the techniques developed will point the way toward development of a fully operational and more effective system for earth resources management.[8]

Since its launch July 23, 1972, ERTS has been providing types of multispectral data that had been heretofore unavailable. The uniqueness of the ERTS multispectral data is especially notable when compared to multispectral data gathered from aircraft missions and manned space flights.

Unlike data gathered by these methods, ERTS provides for repetitive imaging of the same area every eighteen days for the life of the satellite. This is valuable since many images of the same area over time are necessary to monitor changes that influence the earth's resources. The expense

of operating an aircraft make such repetitive coverage uneconomical. Manned space missions can obtain many images of the same area on the earth's surface, but repetitive coverage on a regular basis is rare because manned flights are not scheduled regularly and the duration of each flight is relatively short.

To view the earth's resources in their entirety, ERTS is able to obtain multispectral images on a global basis. This is not possible with aircraft because of the bad weather that is prevalent in some areas and the remoteness of some areas. Both of these factors contribute to make aircraft coverage of areas such as the polar regions uneconomical. Whereas global coverage is possible with manned space flights, the expense of such missions precludes them from gathering data continually.

Perhaps the most important characteristic of ERTS multispectral data is that it affords a synoptic view of large areas (33,000 square kilometers). This is especially important in viewing patterns and interrelationships that exist on the earth's surface. The 914 kilometer orbit (568 statute miles) of the satellite makes this possible. With aircraft data, the coverage is less. An area of approximately 530 square kilometers is imaged by an aircraft at 20,000 meters (65,000 feet) with a VC-10 camera. Whereas large areas have been imaged from manned spacecraft, such images are not as amenable to quantitative analysis because of oblique camera angle and the lack of registration between repetitive images of the same area.

3.2 Description of the ERTS System

In this section a brief description of the systems aboard the satellite is presented. The satellite's pattern of coverage, and the way the images are transmitted back to earth are also discussed.

The spacecraft vehicle consist of the payload subsystems and the various support subsystems. The configuration of the spacecraft is shown in Figure 2. The payloads are the Return Beam Vidicon (RBV) camera system, the Multispectral Scanner (MSS), the Wideband Video Tape Recorders (WBVTR's), and the data collection system.

The RBV camera system and the multispectral scanner are the two imaging systems aboard. The RBV camera system surveys the earth via three co-aligned camera sensors, each viewing the identical scene but in a different spectral band. The viewed ground scene, 185 kilometers square, is stored on the photosensitive surface of the camera tube. After shuttering, the image is scanned by an electron beam to produce a video signal for transmission to ground-based receiving stations.[9]

The MSS is basically an optical-mechanical scanner. The optical energy is sensed in four visible spectral bands. The data is formatted into a single data stream for transmission by a multiplexer. A more detailed description of the MSS is given in the subsequent section.

When the RBV and the MSS are operating withing range of a ground receiving station, their data are transmitted in real time to the ground receiving site and recorded on magnetic tape. The location of receiving stations make it possible to receive imagery data during 11 or 12 of the

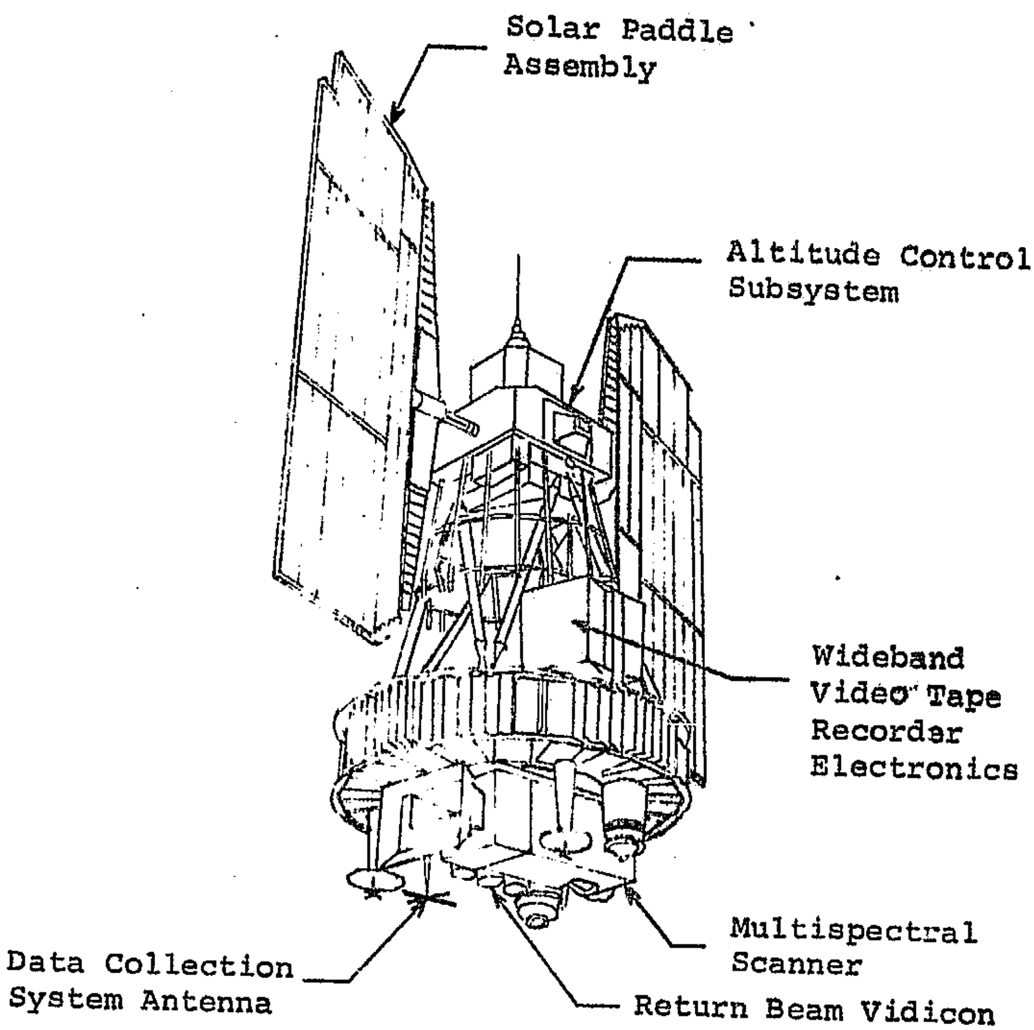

Figure 2. ERTS-I Anatomy

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nearly 14 orbits the satellite makes each day.[10] During orbits when the satellite is not within view, the imagery data is stored temporarily on either of the two wideband video tape recorders.

At present, one of the WBVTR's is inoperable and RBV has been turned off. Early in the mission a power surge temporarily affected the satellite's stabilizing jets and caused the spacecraft to gyrate out of control. To protect the RBV cameras and to locate the problem, the RBV was turned off. Since one of the WBVTR's is inoperable, reducing the satellite's recording capability, the RBV system has yet to be reactivated. If, for some reason, the MSS becomes inoperable, the RBV system could still be used.[11]

To further monitor the earth's resources, the Data Collection System is a part of the payload. This system obtains data from earth-based data collection platforms (DCP's) for transmission back to receiving stations. These DCP's are equipped by specific investigators with as many as eight sensors which sample such environmental conditions as temperature, snow depth, conductivity, or pH. Whenever there is a line of sight view from the satellite to both the DCP and a receiving station, the data is relayed and then made available to the investigator.

To support the payloads there are integrated subsystems that provide the power, control, environment, orbit maintenance, attitude control, and information flow required. Discussion of all subsystems is not necessary but some mention of the attitude control capability of ERTS is warranted since it relates to the quality of the images received. The attitude control subsystem controls the spacecraft with earth-pointing accuracy of less than 0.7 degrees in the axes of

pitch, roll, and yaw. The system uses horizon scanners for pitch and roll control and a gyro-compass for yaw orientation.

To provide systematic, repeating earth coverage under nearly constant observation conditions, the orbit of the spacecraft must be very precise. Consequently, the orbit has been selected and trimmed so that the satellite ground trace repeats its earth coverage at the same local time every 18 day period within 37 kilometers (20 nautical miles). The orbit is nearly circular, such that the earth is consistantly viewed at nearly the same altitude.

The imagery data is transmitted down from the spacecraft and is received at one of three United States stations. One station is at Greenbelt, Maryland; a second at Goldstone, California; and a third near Fairbanks, Alaska. Canada has a fourth station, near Prince Albert in Saskatchewan, which can receive only. All data is processed at the National Aeronautics and Space Administration's Data Processing Facility (NDPF) at the Goddard Space Flight Center near Greenbelt, Maryland.

As mentioned previously, the data from the MSS is encoded into a data stream suitable for real time transmission. Each of the three ground receiving stations is equipped with a demultiplexer which decommutates the data stream into the original scanner channels. These are recorded permanently by digital tape recorders. If the data is received at Goddard it can be processed shortly after reception, but if it is received at the other two stations, the tapes must be transferred to NDPF.

3.3 The Multispectral Scanner

Since the data used in this investigation is from the multispectral scanner, a more detailed description of the system is presented. The 4-band scanner system aboard ERTS was built by the Hughes Aircraft Company. The four selected spectral bands are: band one, 0.5 to 0.6 microns; band two, 0.6 to 0.7 microns; band three, 0.7 to 0.8 microns; and band four, 0.8 to 1.1 microns.

The object plane (the portion of the earth being imaged) is scanned by means of an oscillating flat mirror between the scene and the double-reflector, telescope type of optical chain (Figure 3 and Figure 4). Figure 3 shows the elements of the scanner relative to the orbit. Earth is downward and the velocity of the scanner is away from the reader. As the mirror rotates, a line across the 185 kilometer swath is swept across the focus of the telescope. Six lines are imaged in the four spectral bands during each sweep. These six lines and four bands are defined by a four by six matrix of glass fibers in the focus area of the telescope.[12]

Light impinging on each of the 24 glass fibers is conducted to an individual detector through an optical filter. Each detector is optimized for the particular spectral band served. The signals from the detectors are then sampled, digitized, and formatted into a single high rate bit stream suitable for transmission.

After the scan mirror has swept across the scene it returns to its original position during its retrace cycle. During one complete oscillation of the mirror, the subsatellite point will have moved 474 meters (1,550 feet) along the satellite's ground track. The width of the along-track

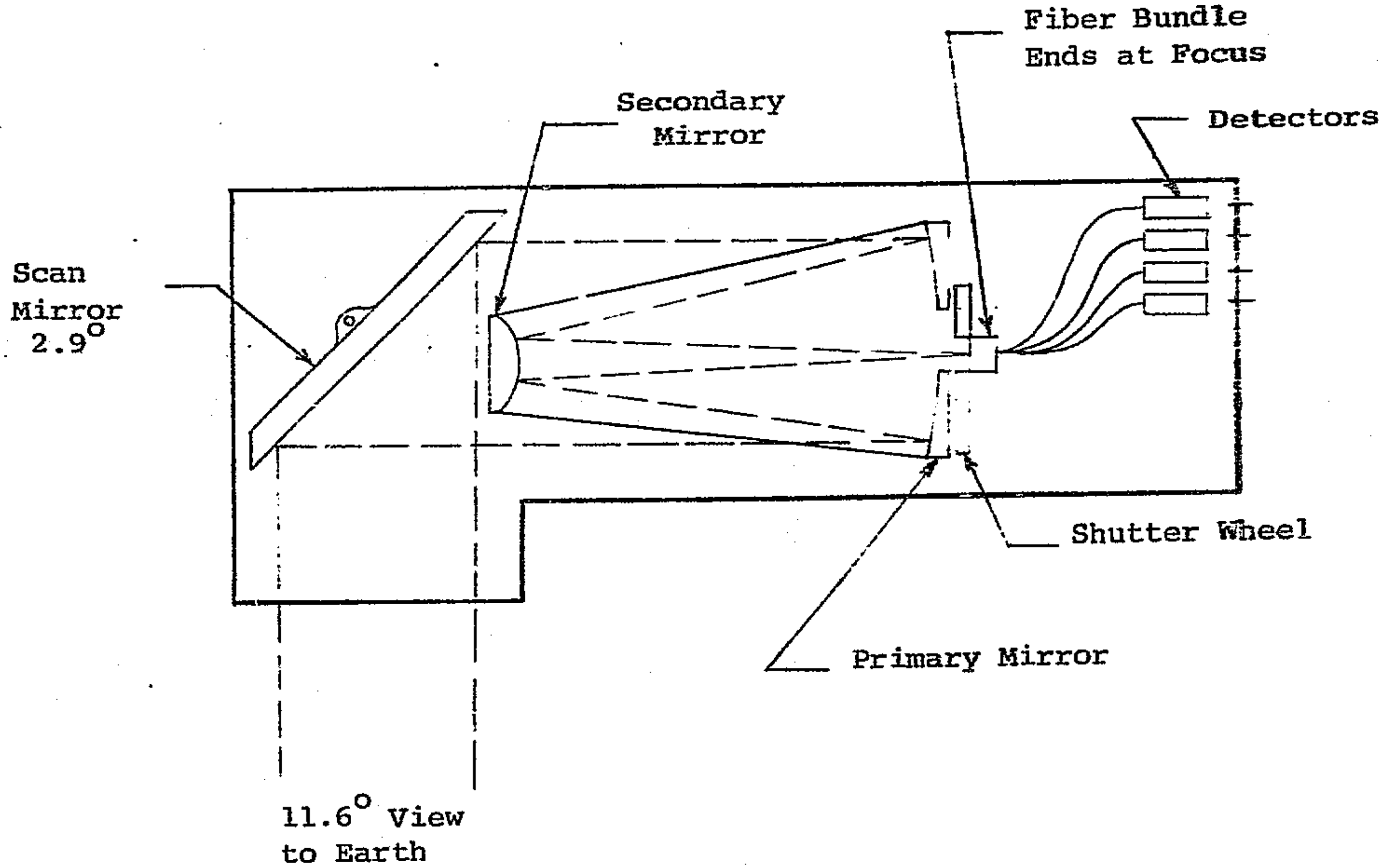


Figure 3. Four-Band Scanner Configuration

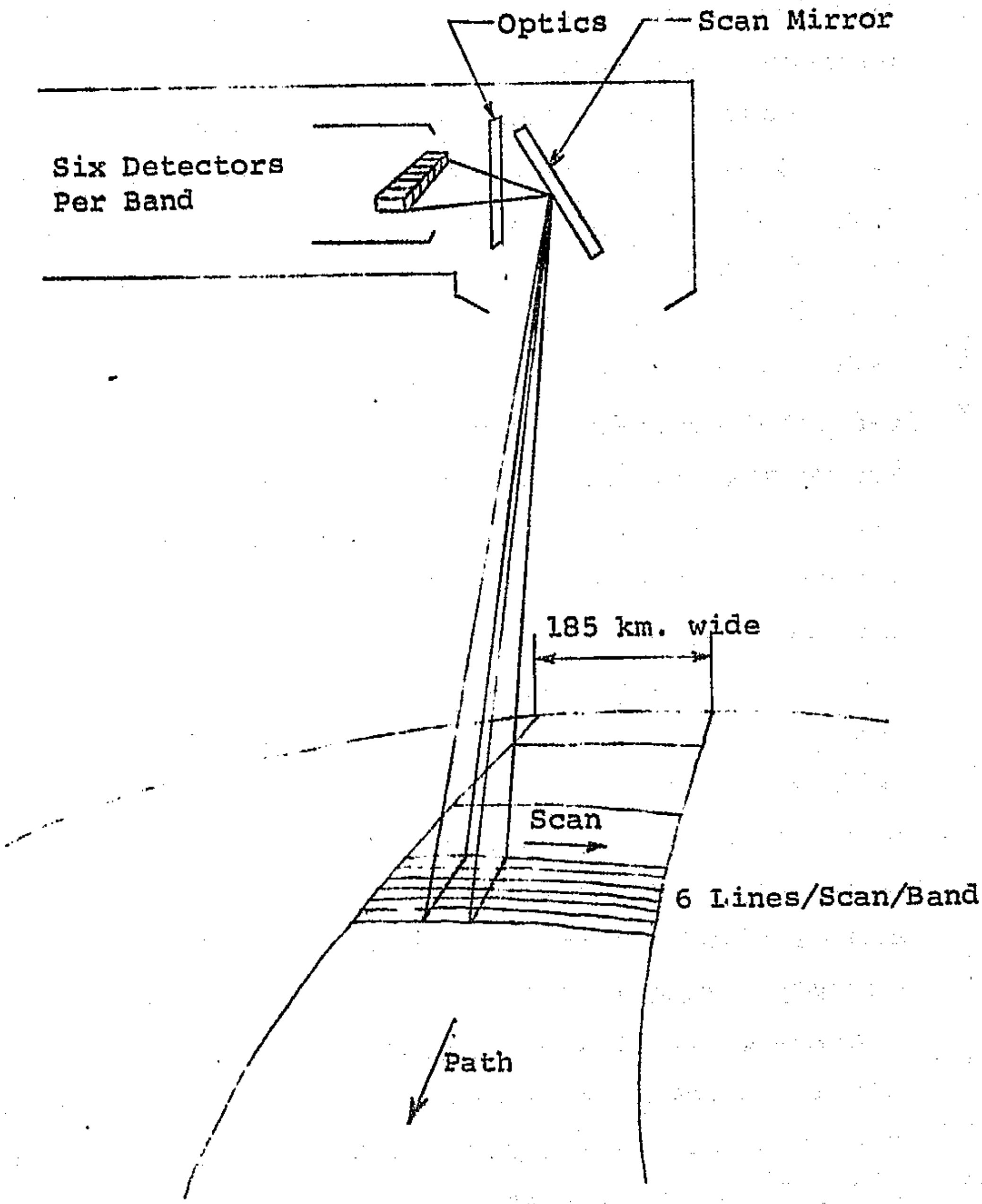


Figure 4. Multispectral Scanner Coverage

field of view of detectors is also 474 meters. Since the sixth scan line of one oscillation is adjacent to the first scan line of the next oscillation, complete coverage of the total 185 kilometer wide swath is obtained.[13] Figure 5 shows the scan pattern.

During the retrace cycle, a shutter wheel closes off the optical fiber view to the earth and a light source is projected onto the fibers for calibration. Since the calibration lamp intensity is constant, it is possible to check the relative radiometetric levels of the detectors. In other words, a check is made to see that the amount of reflected sunlight impinging on the fiber ends during the active scan is being accurately reproduced in terms of the detector's video output. In addition, the sun is flashed across the fiber ends once per orbit so that the calibration lamp is checked.

The inherent characteristics of the MSS system make MSS data especially useful in land-use studies. The MSS system's major shortcoming relative to the RBV system is its inferior geometric accuracy. During the interval over which the MSS is imaging a complete frame, the spacecraft may experience small yaw and attitude variations that degrade geometric accuracy. This is not a problem with the RBV sensor since it makes a full frame snapshot instantaneously.[10] Over the relatively small study areas used in this investigation (approximately 45 square kilometers for a study area compared to 33,000 square kilometers for an ERTS scene) any geometric distortion is far less evident.

In rigorous land-use studies over relatively small study areas, point to point registration of data points in all four bands is necessary. Such registration is basic to

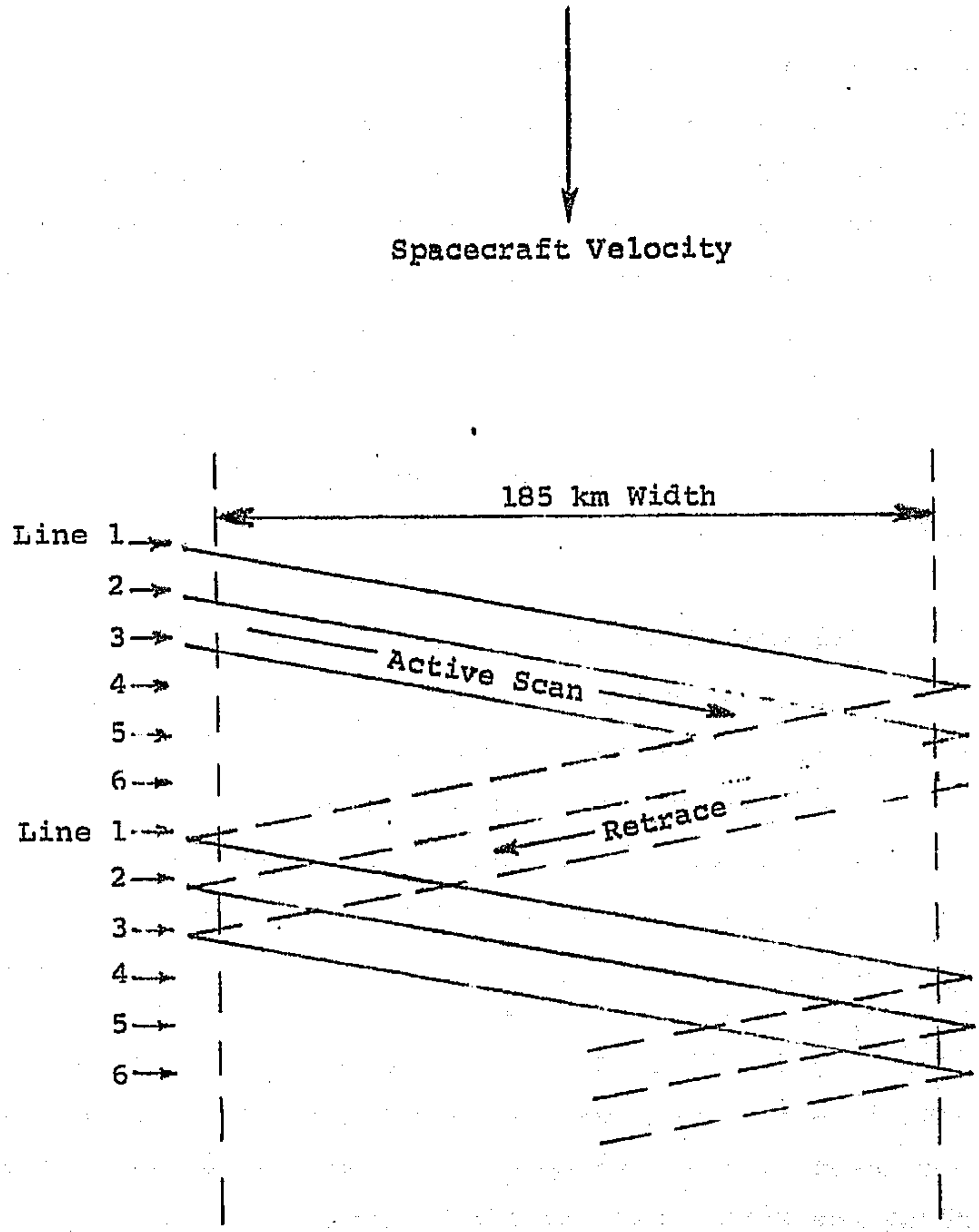


Figure 5. Ground Scan Pattern for a Single Multispectral Scanner Detector

optical-mechanical scanner systems because all spectral channels share common optics. This is not the case for the RBV sensor since three separate cameras are used.

The MSS sensor also has inherently better radiometric accuracy than the RBV type because it uses a few small detectors instead of a large screen surface. The MSS's built in radiometric calibration system test sensitivity after each scan. In addition, the calibration system is periodically checked against the sun's intensity. Although the RBV also uses a calibration lamp arrangement, it does not include solar input.

3.4 ERTS Data Products

A variety of data products are available from NDPF so that investigators may choose the product or products most useful to their specific area of investigation.

The form of the imagery before processing is digital data on magnetic tape. Before this data is transformed into an image, it is corrected to take account of the spacecraft's attitude, rotation, and heading during imaging. Spacecraft telemetry data provides this information as well as the precise time the image was taken. The digital scanner data is processed into scenes covering rhombic areas 185 kilometers along the scan lines and 178 kilometers along the path of the satellite. The rhombic shape is caused by the rotation of the earth beneath the path of the satellite and the scan lines not being perpendicular to the path of the satellite since the end of each scan is 474 meters farther along the path of the satellite than the beginning. These system-corrected images are generated on 70-mm black and white film

rolls. These rolls are used to produce photographic imagery in a variety of formats.

Computer-compatible tapes (CCT's) containing a digital version of the original imagery are also available. However, these tapes do not include the geometric corrections applied to the images. Within the scope of this study, this is not necessarily a drawback since the data's radiometric fidelity is the same, and the study areas are relatively small.

The format of the imagery data on the system corrected CCT's is quite complicated to those unfamiliar with computer technology. It is sufficient to understand the format enough to locate study areas within a scene according to scan line number and sample number.

The digital data is formatted such that there are four CCT's for each ERTS scene. Each tape covers a 46.25 by 178 kilometer strip in the image (Figure 6). By knowing that there are 810 samples per scan line and that there are 2340 scan lines on each tape, any area in the scene can be located according to scan line and sample number by simply locating the area on the corresponding ERTS image, measuring its location, and calculating its scan line and sample number.

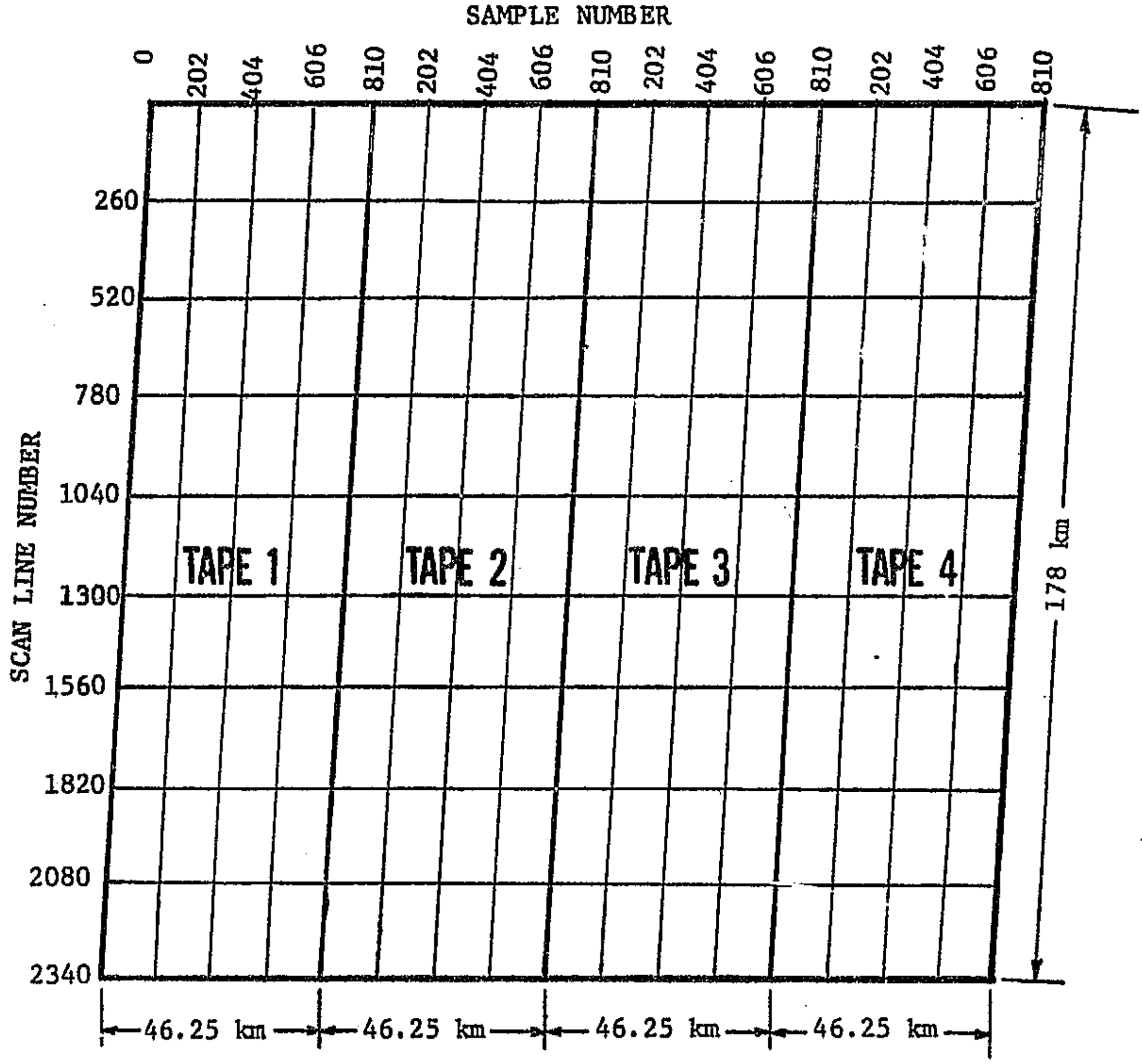


Figure 6. Computer Compatible Tape Coverage of an ERTS Scene

CHAPTER IV

COMPUTER USE IN PROCESSING MULTISPECTRAL DATA

4.1 Data Handling and Storage

Prior to the operation of ERTS, the volume of multispectral scanner generated was relatively small due to the expense of operating scanner systems and an aircraft. With the operation of ERTS the volume of multispectral data being collected overwhelms the current capability to process it into usable data products. In other words, the capability of obtaining data currently exceeds the level of understanding regarding the data.[7] The future outlook indicates that this collection will continue to grow with the prospect of other remote sensing systems such as ERTS-B. In addition, if more sophisticated scanners with better spatial resolution are installed in operational satellite programs, the data output per area will increase compounding the rate at which multispectral data is generated. Handling and processing of this vast amount of data will necessarily require compression of the data into smaller quantities of more meaningful parameters which characterize the physical phenomena recorded by the various sensors.[14]

It is traditionally held that the information contained in multispectral data is in such a complex form that its extraction requires a highly subjective interpretation by a human analyst.[15] The analyst must either be familiar with the spectral characteristics of the land-cover types he is seeking to locate or have the ability to apply extremely complex logic in integrating the reflectance readings from numerous sensors into a decision. Clearly, this process is both time consuming and subjective, characteristics not compatible with the current situation.

A new approach assumes that an electronic system can recognize patterns in the data and compress it into a more managable form. Thus a new concept in remote sensing is envisioned whereby a multispectral sensor system would not only include the sensors with their individual outputs, but also the processing necessary to produce a final single product.[15] Consequently, computers will undoubtedly be required to do a considerable portion of data reduction and analysis.

4.2 Pattern Recognition Research

Researchers in pattern recognition seek to exploit the spectral information of imagery or of spectral scanners for extracting information through methods based entirely on a set of mathematical rules which can be implemented into computer techniques. Many techniques have been developed. Each have specific advantages and disadvantages which limit each technique to certain applications. These techniques may be divided into three broad classes. Unlike unsupervised classification techniques, the first two classes of

techniques require either human intervention or prior information concerning the features being extracted. It would be difficult to integrate such techniques into a system of data compression. Consequently they will not be discussed in any detail.

4.3 Types of Classification Techniques

4.3.1 Feature Matching Techniques

One approach is to use a data bank. In this method it is assumed that all areas considered to have a particular type of land cover, have the same spectral signature. The spectral signature is the combination of reflectance readings from the spectral bands that indicate the characteristics of the land cover. From this assumption, the statistics of the spectral signatures of known land-cover types are derived and stored in a data bank. A comparison of signatures from the resolution elements to those in the data bank classifies each element as to its land-cover type.

The difficulty with this method is that fairly homogeneous areas of land cover are assumed, each with a particular spectral signature. In reality there is appreciable variability in the signatures due to shadows, variations in topography, and scanner look angle. Other serious drawbacks to this technique are the amount of computer memory required to compare an unknown spectral signature with all possible signatures stored in the data bank.

4.3.2 Supervised Techniques

Probably the most popular and widely used techniques can be termed supervised classification techniques since they require human intervention in the selection of training areas. These methods have been used primarily for the analysis of aircraft survey data from a multispectral scanner over agricultural areas. The statistical methods have been developed by investigators at the University of Michigan[16], Purdue University[17], and the University of Kansas.[18]

The data is organized so that each data point or resolution element is addressed by a scan line number and a sample number. Each resolution element's spectral characteristics are represented by a n-dimensional vector whose components are the reflectance readings in each of the n-spectral bands. A boundary map of the area is produced over the grid of resolution elements showing boundaries that delimit homogeneous areas and this is compared with an aerial photograph taken at the same time the data was collected. This allows the observer to select training areas that represent the various types of land cover in the area. These training areas are located according to their scan line and sample number, and the statistics of the area's spectral characteristics calculated.

For identification of crops or land use in each training area, ground truth information is required. After each training area is properly identified, a statistical decision rule is used for classifying the remaining data. A computer map of the ground scene is then printed out showing the location of all data points that were classified according to

the decision rule as belonging to or being similar to the particular training areas selected. This is compared with ground truth for accuracy.

There are many major difficulties with this method. The basis of classification for resolution elements is the similarity of their spectral characteristics to that of training areas representing the land-use categories to be recognized. Such techniques assume that all objects of a given class have substantially the same spectral radiance. Previous studies of a Yellowstone National Park test site and unpublished data have proven this assumption invalid.[19]

It is not uncommon for investigators to report accuracies as high as 80 to 90 percent.[20] Actually such results are only obtained under ideal conditions such as selected level regions of agricultural fields and then only through an iterative process. If the initial classification accuracy is unsatisfactory, this is attributed to the poor choice of training areas. The data is then partitioned again in hope that the new training set is more "representative", until the required recognition is attained, albeit at the expense of arrant violation of good statistical sampling practice.

This transgression is compounded by the fact that the size of the training area in most experiments reported is of the same order of magnitude as the test area, a situation hardly likely to occur in the proposed application to satellite data. It must be concluded that the extrapolation of results obtained under such circumstances to low-resolution satellite data collected without regard to atmospheric disturbances and to the varigated conditions of the areas under inspection is pure speculation.[21]

4.3.3 Unsupervised Techniques

Because of the need to streamline the extraction of information from the rapidly increasing amount of multispectral data being collected, much emphasis is being placed on the development of unsupervised techniques for feature extraction which are designed to extract features from remotely sensed data without either the assistance and supervision of an observer, or the prior benefit of ground-truth information. These unsupervised techniques, often referred to as clustering techniques, extract information by grouping the resolution elements into relatively homogeneous groups and then showing the location and distribution of the extracted land-cover categories on a digital map.

As in other interpretation techniques, ground truth information must be collected. In all other techniques, however, the decision as to the location of the collected ground truth and as to the types of features that will be extracted is made by someone prior to the actual classification taking place. In an unsupervised technique, the classification determines the locations for which ground truth is needed and the data itself determines what types of features can be extracted. Consequently, the exact locations of needed ground truth information can be determined before any is collected and only spectrally discernable features will be grouped into classes. The adequate determination of where and how much ground truth to collect is an important economic consideration when data must be processed on a regional scale. Therefore, this unique characteristic of unsupervised techniques becomes an important consideration as data for large areas is processed.

Compared to other classification techniques, a high degree of classification accuracy is often difficult to obtain and the computer time is relatively extensive when an unsupervised technique is applied. Consequently, the primary thrust of research in this field has been to minimize these disadvantages by developing techniques which optimize the speed of classification while obtaining classifications of acceptable accuracy.

The goal of clustering is either the definition of homogeneous areas of geometrically continguous resolution elements without regard to elements in non-contiguous regions or the partitioning of all statistically similar data points into classes without regard to continuity. An excellent example of the former type of method is the technique developed by Robert Jayroe of Marshall Space Flight Center.[20]

The first stage in his technique is to produce a boundary map of the data by separating the data into homogeneous and inhomogeneous areas. The computer goes through the data sequentially and computes the change present in the data from one resolution element to the next. When the change is greater than the average spectral change, the resolution element is classified as a boundary. The second stage is concerned with the selection and spatial merging of unknown features such that the boundaries on the map are closed and the data within each one is homogeneous. The third step involves describing the spectral characteristics of the resolution elements within each homogeneous area and using this in the final stage to classify the data from the non-homogeneous areas. The final product is a digital image of the ground scene showing the location and distribution of all land use categories.

In the second type of clustering method as in supervised techniques, the spectral characteristics of each resolution element are generally represented by an n-dimensional vector in n-dimensional space (section 4.3.2). The location of the head of each vector in n-dimensional space is indicative of the spectral characteristics of each resolution element. Vector heads or data points that tend to cluster together have similar characteristics and should be grouped together as a class. Various mathematical methods have been devised and implemented into computer programs to locate these clusters in multi-dimensional space, determine the characteristics of these clusters, and by so doing classify the resolution elements.

Two such methods were the basis of the composite sequential clustering technique. Instead of describing a typical technique in this chapter, the description of these two techniques in the following chapter should provide adequate insight into the nature of such clustering methods.

CHAPTER V

THE COMPOSITE SEQUENTIAL CLUSTERING TECHNIQUE

5.1 Introduction

The composite sequential clustering technique is an unsupervised method of classifying data points into spectrally homogeneous classes. The technique was devised by M. Y. Su of Northrop Services, Inc. for the George C. Marshall Space Flight Center. It was designed and them implemented in a digital computer program to classify multispectral data from both aircraft and satellite surveys.

The composite sequential clustering technique is a composite of two independent classification methods. The first method test groups of six or more data points throughout the entire data sequence for similarity, forming classes or clusters in a one-pass sequential analysis. The second technique is an iterative scheme of improving estimated cluster centers. Although each of the techniques can be used separately for processing a given set of data, a composite of the two methods, drawing on the merits of each, can classify data more accurately.[22]

Descriptions of these two clustering algorithms separately and then the integration of these two into the composite sequential clustering technique are presented in the following subsections.

5.2 Statistical Sequential Clustering (SSC)

The SSC program classifies a sequence of multispectral data into a specified number of subclasses. To accomplish this, the program consist of four main steps:

Establishing new classes

Classifying new samples into established classes

Merging excessive classes

Displaying classification map and statistics.

Spectrally homogeneous classes are established by the performance of a statistical test for similarity on a group of six or more data points. If the program is set to test six points at a time, the first six data points in the sequence are read and tested for homogeneity. If the test is positive, a new class is formed. If the test is negative, the first point is discarded as unidentifiable data and the next data point in the sequence is read. This new group is then tested. As long as the result of the test is negative, this process is repeated. After the first class is established and its statistics calculated (mean vectors, standard deviations, etc.) each subsequent data point is tested against it to see if the point belongs to that class. In cases where the data point does belong to that class, the class' statistics are updated. Those samples not belonging to the existing class are held with other unclassified data until six unclassified data points are collected. The test

for homogeneity is then performed on this group. If the test is positive, a second class is formed and its statistics calculated. If the data tested does not comprise the second class, the first data point held is discarded as unidentifiable to allow for the testing of a different group formed by the replacement of the discarded data point. This procedure is repeated until the second class is formed. Thereafter each subsequent data point is tested against both classes and either classified with one of them or held with unclassified data until there are enough data points (six) to test for a new class. Thereby additional classes are formed by the same procedure until the designated number of classes is reached.

After the establishment of each new class, a test is made to determine whether the number of classes is greater than the number designated. If this number has been exceeded, the number of classes is reduced back to the maximum number by combining the two populations that are most similar to each other.

The classification is complete after the last data point in the sequence has been processed. The program then prints out the number of data points, the mean, the variance of the spectral intensity for each class, and a two-dimensional map of the spatial locations of data points in each class, each designated by a different alphanumeric symbol.

5.3 Generalized K-Means Clustering (GKMC)

As mentioned in the previous chapter every data point can be thought of as a point in multi-dimensional space, the components of the vector to that point being the readings in

each of the spectral bands. In the case of ERTS there would be points in four-dimensional space since ERTS imagery is collected in four spectral bands. The GKMC is another way of defining the clusters that exist in the data.

The GKMC program is an iterative technique of improving estimated cluster centers for the purpose of establishing spectrally homogeneous clusters or classes within the data. The technique consist of four steps:

Estimation of new cluster centers

Preliminary improvement of cluster centers

Final improvement of cluster centers

Display of results in classification map and statistical parameters.

The speed at which this iterative process converges on the final clusters and the accuracy of classification depends primarily on the choice of the initial cluster centers. If the initial locations are poor approximations of where the cluster centers really are, more iterations will be needed for convergence. Consequently, it is desirable that the initial cluster centers be distributed over the populated region of the feature space rather than concentrated in one part of it. One procedure used to obtain such a distribution is as follows. The first data point in the sequence is designated cluster center one. The distances of the remaining points from this one are calculated, and the fartherest point is designated cluster center two. The smaller of the two distances from every data point to these two initial cluster centers is listed, and the data point having the greatest minimum distance is selected as cluster center number three. Other initial cluster centers are chosen in turn to have maximum separation from the existing centers

until the prescribed number of cluster centers (one for each class) is estimated. The result is initial cluster centers well scattered over the range of data points.

The next step is to improve the initial cluster centers such that they represent the mid-points of the clusters in the data. Each data point is first classified with one of the estimated cluster centers. This is done by calculating the distance of each point with respect to every cluster center and assigning data points to the particular class that yields the minimum distance. Once this is done, the location of the data points in each class is averaged to give the updated mean spectral vector. These updated cluster centers are regarded as the new initial cluster centers for the next iteration. The procedure is repeated until the distance between two successive iterated values of every cluster center is smaller than some prescribed threshhold value, or until some fixed number of iterations is performed.

A final improvement of the cluster centers is necessary. The reason is shown in Figure 7. In this figure, three clusters are shown in two dimensional space. The best results obtainable, after a sufficient number of iterations, is shown by the linear minimum-distance decision boundary as indicated by the solid lines. Some points actually belonging to cluster number one are misclassified into cluster number two or number three. This is because the intradistance of cluster number one (the distance to the farthermost sample) is greater than half the distance between centers of cluster number one and cluster number two.

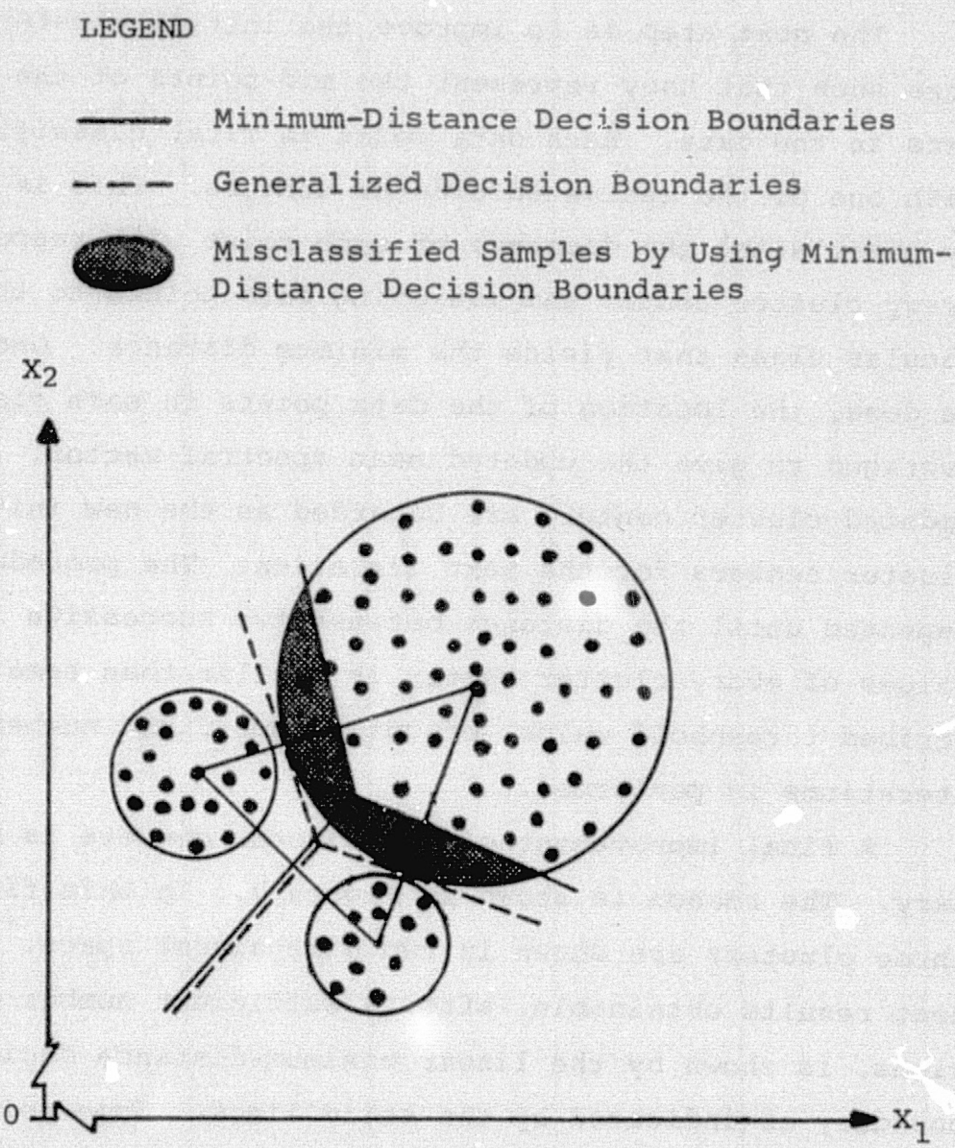


Figure 7. Comparison of the Minimum-Distance and Generalized K-Means Decision Boundaries

To rectify this difficulty, a method must be devised whereby the intracluster distance is a consideration in the placement of the decision boundaries. The standard deviation vector of each cluster is one measure of the intracluster distance. Each component of the vector to a cluster center has a standard deviation and the standard deviation vector is the resultant of these standard deviations. If the clusters contain random distributions of points (the clusters are spherical and not elongated) each component of the standard deviation vector would be approximately equal and the standard deviation vector may be characterized by a single scalar. These standard deviations are used as weights to place generalized decision hyperplanes in multidimensional space such that they are sensitive to the intra-distance in the clusters. Hence, after the clusters have been improved as best they can by the first criterion, the last iteration is done using the standard deviations.

Clearly, decision hyperplanes placed by this technique classify the samples more accurately. It would seem that this method could be used exclusively and the minimum distance criteria eliminated. However, decision hyperplanes placed by the generalized criterion are accurate if the standard deviations correctly characterize the clusters. The standard deviations calculated during the first few iterations are very inaccurate since, at that point, the cluster locations are only educated estimates and a great number of the samples are still misclassified. In fact, there is no strong reason to expect better performance from the generalized criterion during the first few iterations.[22] On the other hand, if the minimum-distance criterion is used to its utmost capacity first, a better

estimate of the standard deviations can be obtained and the second method can be used effectively.

The final part of the GKMC technique displays the results. A two-dimensional map is produced consisting of alphanumeric symbols designating each class that was formed. Each class is described statistically in much the same manner as the output of the SSC technique.

5.4 Composite Statistical Sequential Clustering

The two unsupervised techniques described each have specific advantages and limitations. The single most significant advantage of the SSC program is that it requires only one pass of the entire data sequence to achieve fairly good clustering of the given data. This truly sequential feature is unique among existing clustering techniques. However, because there is only one pass of the data sequence, the class of those unidentifiable data points that are passed over during establishing new classes cannot be reexamined. This is the main drawback of the SSC technique.

The most significant advantage of the GKMC technique is that it possesses the capability for repetitive correction and updating of the established cluster centers. Its main drawback is the difficulty in choosing the initial cluster centers. A completely arbitrary selection results in very inaccurate estimates requiring many iterations to achieve good clustering accuracy. If the cluster centers are estimated such that they are well distributed over the range of the data, many passes of the entire data sequence must be made.

From the preceeding assessment of these two techniques, it is clear that they can complement each other since the drawbacks of each technique can be eliminated by properly combining the two techniques. The composite sequential clustering technique is then composed of two steps:

> The given data sequence is processed by the SSC technique with only a single pass of the data sequence. The outputs of the processing will be the mean spectral vectors to the cluster centers.
>
> The mean spectral vectors from the first step are used as the initial cluster centers for the GKMC technique. To allow for extra cluster centers from the unidentified samples of the SSC, extra initial cluster centers may be estimated using the first step of the GKMC. Finally, the initial cluster centers are iterated two or three times to obtain the final clustering.[22]

Unlike the GKMC technique relatively few passes of the data sequence are required and unlike the SSC technique, no data is passed over in the analysis.

5.5 Present Form of CSC Technique

The preceeding description of the CSC technique applies to the original program designed by M. Y. Su. The present form of the technique is somewhat different.

In the original technique there are two methods for establishing initial cluster centers. The primary method is the use of the SSC technique while another method allows for establishing extra initial cluster centers for clusters which may exist in the data unidentified by the SSC technique. In the present computer program there is no provision for establishing extra initial cluster centers. Consequently, the total number of classes produced by the

technique will be no more than the number of classes produced by the SSC technique.

The original technique was designed to classify all data into one of the established classes. This feature resulted in some data points as far as five or six standard deviations away from the cluster center being classified as part of the class represented by the cluster center.[23] Data points this far from the mean are better described as unclassifiable since the spectral signatures of such areas do not cluster closely with any group of data. To rectify this difficulty, all data points beyond three standard deviations of any cluster center are now considered as unclassifiable and are represented by blank spaces on the digital map of the classification results.

CHAPTER VI

DESCRIPTION OF STUDY AREAS

6.1 Selection Criteria

To effectively evaluate the utility of using the composite sequential clustering technique for the unsupervised classification of land use from ERTS data, several representative situations should be investigated. Many factors determine the reflectance that is measured by ERTS. These include the characteristics of the ground cover, the slope or ruggedness of the terrain, and the presence of atmospheric conditions such as clouds and haze. Occasionally, malfunctions in the ERTS system cause grossly inaccurate or "bad" data to be generated. The presence of this "bad" data is one more variable that must be considered.

The region's ground cover was the primary criterion in the selection of study areas. Several aspects of the region's ground cover were considered.

The apparent number of land cover types in the region was noted and the study areas were then chosen such that the diversity of land use varied between study areas. This was done to evaluate the method's ability to detect slight differences in ground cover as manifest in the number of land-use classes generated.

Another variable affecting the utility of the ERTS data and the performance of the clustering technique is the region's areal complexity. A simple area is defined as having large contiguous areas of homogeneous land use while a complex area is defined as having many small areas of homogeneous land use. Although identical land use may exist in two areas, a great difference in areal complexity would have a definite affect on the ERTS data and in its classification.

To understand this effect, it must be noted that ERTS gathers reflectance data for an area about the size of an acre. In very complex regions, the likelihood of more than one type of land use residing in any one acre is far greater than for a simpler region. Consequently, the likelihood that an ERTS data point represents a composite of more than one land use is far greater in complex regions. The presence of these "composite" data points is important in that they may be unclassifiable and distort the classification.

The size of homogeneous areas also directly affects the performance of the clustering technique. In complex regions, the reflectance values change more often since the land being imaged is rarely the same for long distances along a scan line. In the first part of the CSC technique, this sequential variability affects the establishment of initial cluster centers. Since the CSC technique tests groups of data points, it is important that the number of data points tested be compatible with the variability of the data and still include enough data so that the statistical test for similarity can be used with some confidence that those classes which are established are representative of the data. If many homogeneous areas are represented by

no more than four contiguous data points, it would be illogical to test groups of six data points for similarity. The technique would not be sensitive enough to detect the small homogeneous area. The second part of the clustering technique will rectify this difficulty if somewhere in the data there are six data points of that land use recognizable as a separate class by the SSC technique (Section 5.2). If not, then this particular land-use class, although spectrally discernable by ERTS, and although perhaps covering a considerable portion of the study area, would be left unclassified simply because it was broken up into small homogeneous areas. On the other hand, testing too few data points would result in cluster centers being established which actually do not exist since smaller groups of data points are less representative of the entire population. Therefore, less confidence can be assigned to the results of the test when smaller groups of data are used. Consequently, both complex and simple study areas were chosen for analysis.

As many types of land use as possible were included in the selection of study areas so that many different spectral signatures could be evaluated. By including many types of land use in the analysis, those types of land use not discernable with the technique and those types of land use easily misclassified were isolated.

The study areas were chosen such that land with both moderate and severe slope was represented. Since the amount of light reflected not only depends on the surface characteristics but also on the angle at which light strikes the surface, land sloped such that the sun's rays are reflected

directly toward the ERTS satellite will have higher reflectance values than identical land sloped such that very little of the sun's energy reaches it. To study this effect, especially rugged land was included in the study areas.

A large percentage of all ERTS imagery for the Tuscaloosa area includes clouds and haze. Although in many cases the area is totally obscured, quite often the cloud cover is sparse and scattered. Since the presence of several small clouds in an area may not preclude its usefulness, and since completely cloud free imagery cannot be depended on, the effect of clouds upon an unsupervised classification technique is a valid point to study. Consequently, several small clouds were included in some areas analyzed.

As mentioned in section 3.3, six scan lines are imaged with each sweep of the oscillating mirror. Occasionally there is a malfunction in the system such that inaccurate data is generated by one of the six sensors. When this happens, these lines of "bad" data appear as regularly spaced miscolored scan lines or as "bands" on the image. This effect is not readily apparent to the untrained eye and initial examination of ERTS data suitable for analysis did not detect its presence. However, when all ERTS imagery suitable for this study was examined for this "banding" effect and it was found to be present on all imagery. In view of the fact that this is obviously common in ERTS imagery, and since no suitable imagery free of "banding" was available, this situation, by necessity, was studied.

As the areas were delimited, care was taken to satisfy as many of the criteria as possible while minimizing size.

By so doing, the computer time for processing the ERTS data was held to a minimum and more comprehensive analysis was applied to the results.

A final consideration was necessary in the location of the areas. The ERTS data is processed in the form of 11.5 kilometer strips. If the study areas are entirely contained within a single strip, processing time can be reduced.

6.2 Study Area One--Stripped Area

Study area one is in west-central Tuscaloosa County astride the portion of the Black Warrior River impounded by the Holt Lock and Dam (Figure 8). The area is in the shape of a rhomboid, the corners of which are located at (UTM) coordinates 45996886, 46986872, 46886813, and 45846829.

This area is very isolated. Only two public roads are in the area. One road goes through the area's southwest corner and serves Holt Lock and Dam and the Deerlick Creek public use area. The other road enters the area from the south and goes to a small farm in the south-central portion of the area. The remainder of the roads are either small logging roads or roads serving strip mines.

Initial analysis of high altitude photography resulted in an estimate that the area had a maximum of six different land-use categories. Examination of the area on ERTS imagery showed the presence of scattered clouds. Thus, the addition of a class for clouds and another class for cloud shadows resulted in a maximum of eight categories from the unsupervised classification. This estimate was used as the maximum number of classes requested on the data processing request.

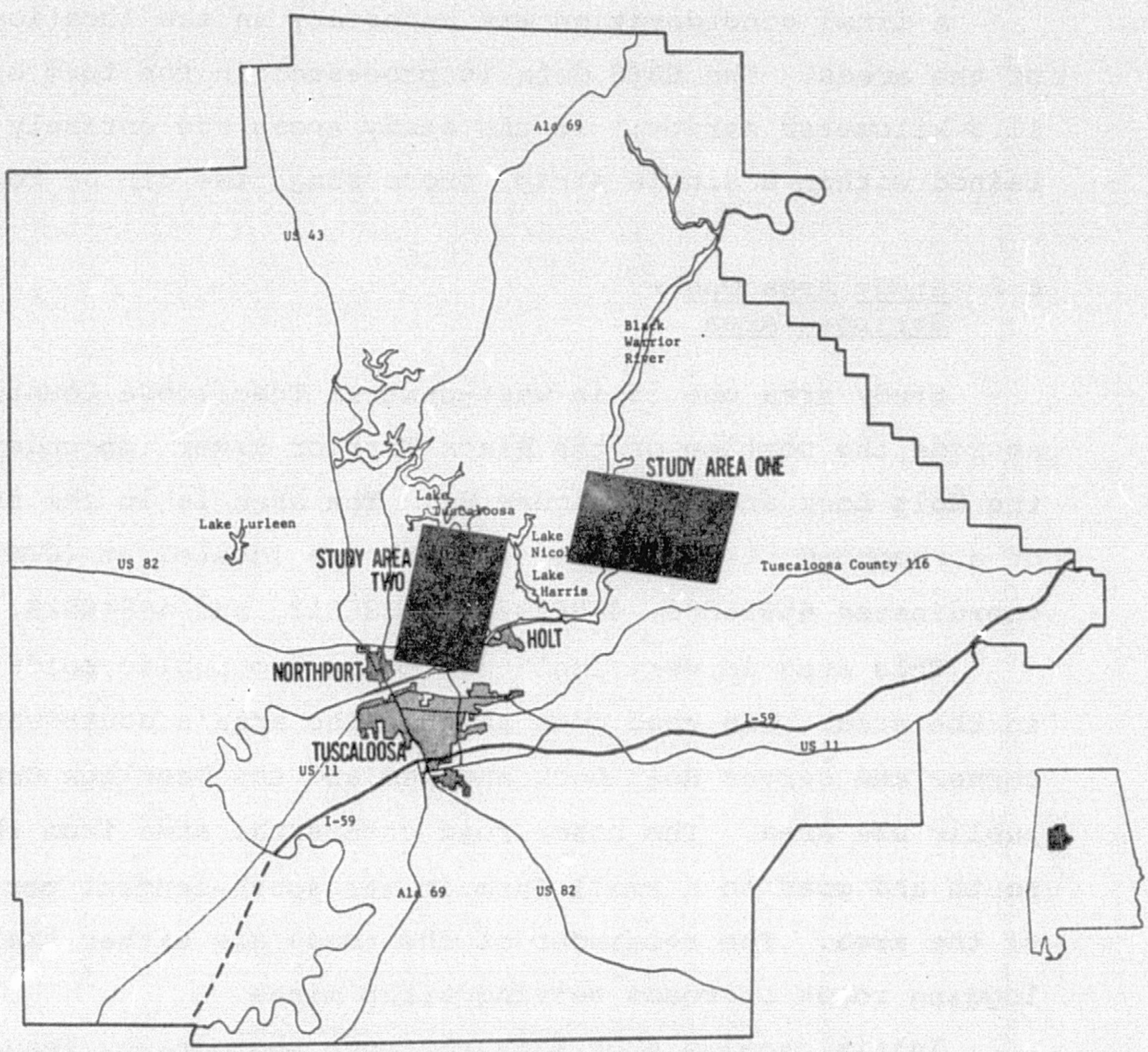


Figure 8. Location of Study Areas in Tuscaloosa County, Alabama

The forest in the area was divided into two classes. This was done to account for the expected variation of reflectance within the forested areas caused by the presence of both deciduous and pine trees as well as the variable density of trees throughout the forest. The locations of both types of trees were evident on the winter air photo coverage. The deciduous forest forms a pattern conforming to the valleys while the pine and mixed forest are found on the hills. The deciduous trees were completely defoliated and presented a different spectral response compared to the pine trees which had foliage. The areas of low density were found primarily in logging areas where the forest had been thinned by tree harvesting. These areas were recognized by a characteristic color on the air photos caused by the soil and underbrush being exposed and by the patterns formed by the logging roads.

Two small areas of agriculture are in the area. The winter coverage showed all of the fields to be untilled and idle. The spring underflight coverage showed some of these fields had been tilled but there was no evidence of crops. To ascertain the time when these fields were tilled, the United States Agriculture Stabilization and Conservation Service was consulted. According to ASCS personnel, heavy rains made cultivation impossible except for a period of no rain from March 23 until early April when some tilling was done. The ASCS personnel were confident that tilling was done before March 28th, the day of the ERTS pass.

The spring underflight coverage was not available when the initial analysis was made, so the need for a class representing barren soil was not known. Thus only one land-cover category was expected from agriculture.

The most notable features in the area are the strip mines. These areas are composed primarily of sandstone and shale exposed by the strip mining of coal. One class was allowed for the strip mines.

Two classes were allowed for the water to account for the vast difference in water quality between the water in the Black Warrior River and the water standing in the strip pits. Observation showed the water in the strip pits to be a green color as compared to the dull blue color of the river. The water in the river is relatively clean while the water in the strip pits is discolored by iron sulfate or hydroxide. Since different reflectance values can be expected from water bodies of various qualities, two separate classes were allowed for surface water.[23]

As can be seen by examination of Figure 9, the terrain in this area is quite rugged. The hills are accentuated by shadows since the photo was taken when the sun was at a low angle. Examination of a United States Geological Survey map showed slopes to be as steep as fifty percent in some portions of the area. Consequently, the area served as an excellent indicator of the distortion caused by severe slopes.

Although this area contains very few types of land use and the homogeneous areas are large, the areal complexity of study area one is high. This is due to the presence of clouds, severe slopes, and trees with different spectral response. All of these factors distort the spectral response within an area of homogeneous land use and introduce considerable variability in the data.

In summary, this area is representative of unpopulated portions of the county that have been developed as strip

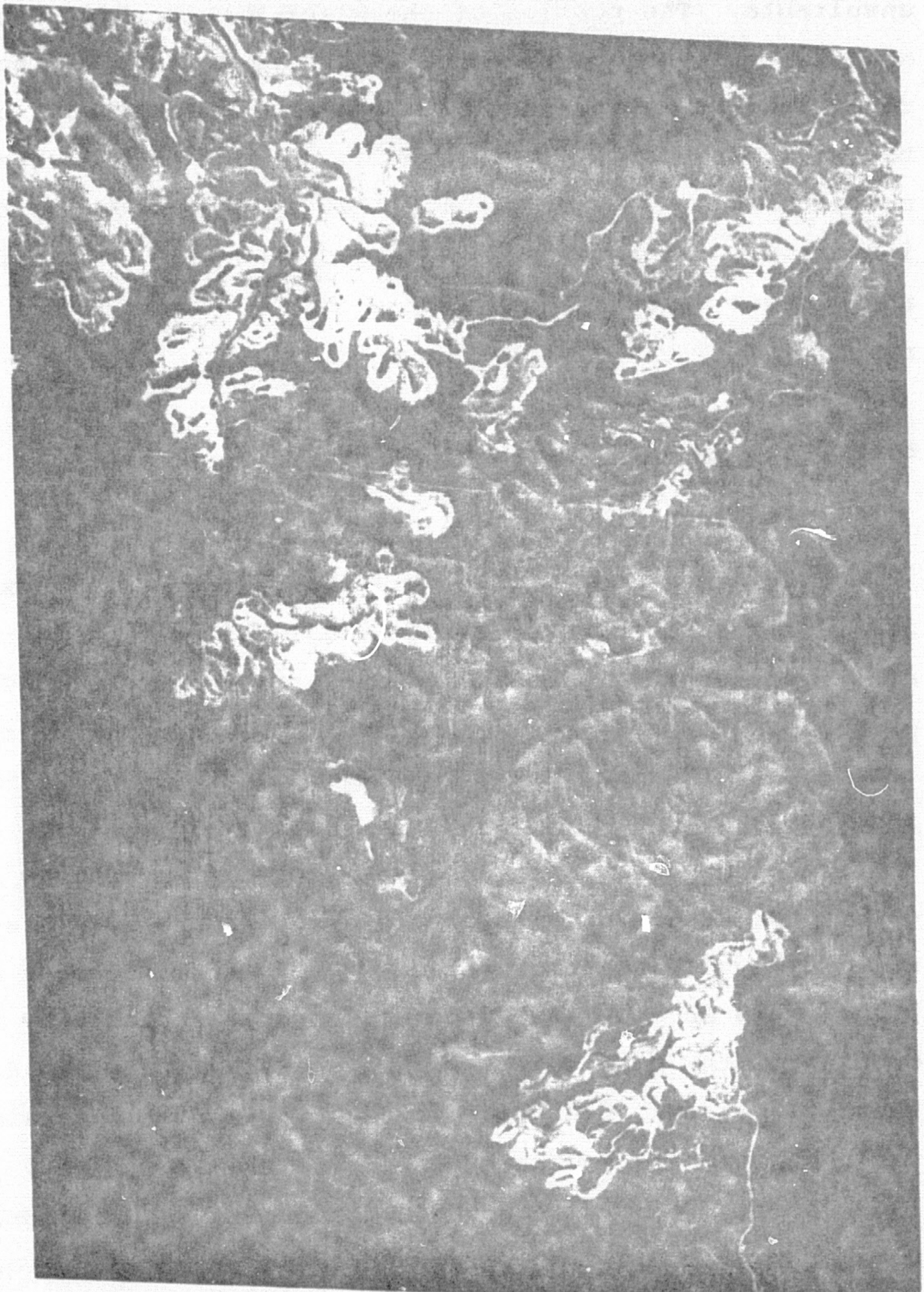


Figure 9. Air Photo of Study Area One

mining and logging areas. Agriculture is secondary primarily because the ruggedness of the terrain makes the land unsuitable. The portion of the Black Warrior River in the area is representative of the impounded portion of the river that runs from the Holt Lock and Dam northward until the river leaves the county. This portion of the river is characterized by water quality that is unaffected by the industrial discharges near Tuscaloosa as well as considerably larger size as compared to other sections of the river.[24]

6.3 Study Area Two--Southwest Lake Tuscaloosa

Study area two is in central Tuscaloosa County extending from the southern third of Lake Tuscaloosa to the northern fringe of the Tuscaloosa urban area (Figure 8). The area is in the shape of a rhomboid the corners of which are located at UTM coordinates 44916835, 45426826, 45226758, and 44696766.

The land in this study area is used in a variety of ways. The southern third of the area (Figure 10) is a rapidly developing suburban section of the Tuscaloosa urban area. This development was prompted only recently by the opening of the U. S. Highway 82 by-pass in 1963. This heavily traveled, four-lane thoroughfare around Tuscaloosa is in the extreme southern section of the study area. In 1969, North River was impounded to form Lake Tuscaloosa, a popular recreation spot. This has also prompted the growth of Tuscaloosa to the north.

Figure 10. Air Photo of Study Area Two

The remainder of the area is composed primarily of agricultural fields, pastures, small farms, and forest. The size of the individual fields vary from over a half square kilometer (125 acres) to small gardens. The borders of many fields and location of some roads tend to follow the township and range lines. Consequently, except where drainage patterns or the location of roads break the pattern, the fields tend to form rectangles.

Small farms border the roads. These areas include trees, grass, barren land, gardens, and buildings clustered together in a relatively small area.

Both deciduous and pine forest reside in this study area. In most cases, the pine are restricted to high areas separated by deciduous and mixed forest. In some cases, however, high density pine forest of uniform height reside in regularly shaped plots indicating areas under cultivation for subsequent harvesting.

There are two major bodies of water in the area. Lake Tuscaloosa is in the northeast section of the area. The Black Warrior River is located in the southeast section of the area. In addition to these primary locations of surface water, there are numerous small ponds and reservoirs throughout the area.

There is one example of a large industry in the study area. One of Gulf States Paper Corporation's pulp and paper mills is located on the south bank of the Black Warrior River on the eastern edge of the study area.

Because of the diversity of land use it was difficult to make an accurate estimate of how many classes would be generated by the CSC technique. Since the technique will

establish no more classes than are spectrally discernable in the ERTS data, an unusually high limit (25) was set on the number of classes produced. Since the estimated number of classes was so arbitrary, the expected ground cover categories are discussed in only general terms.

The variety and the density of trees were considered primary determinates in the classification of the forest. Tree type was mapped from airphotos. Although differences in density could not be quantified into a map, this variable as well as tree type was expected to influence the classification of forest.

The water quality characteristics of the area's surface water are variable. Lake Tuscaloosa, whose primary purpose is domestic water supply, is unaffected by any major sources of pollution. The portion of the Black Warrior River under analysis is affected by the industrial waste of six industries immediately up river.[24] To account for any affect the difference in water quality might have on the classification, more than one class was allowed for water.

Because of the rapid development in the area, there were several areas where soil had been exposed at the time of photography. Several areas were barren because of construction in the area while others had been used as a source of fill material. These barren areas are located along major roads and in the vicinity of the North River Dam.

Urban areas were classed according to their groundcover characteristics. One type of urban land was characterized by high density development. The buildings were close together and there was a complete absence of foliage. The other types of urban land were characterized by various

various densities of development on land covered by forest, grass, or some combination thereof.

Several photographic tones were evident in the fields and pastures indicating a variety of conditions. Tilled fields contained no vegetation while fields which had recently been under cultivation but had not yet been tilled, were covered by the dead stalks and plants left after the harvest. Fields not used for agriculture or grazing were covered by high grass and shrubs. Pastures used for grazing were covered by shorter grass. In residential areas, the well kept lawns represented another type of photographic tone on the air photos. Consequently, quite a diversity of land-use categories were allowed for these non-forested areas.

The terrain in this area is characterized by moderate slope. The most severe slopes are only about twenty percent and these are rare. Therefore, the distortion that this may introduce in the classification was not expected to be significant.

Although a considerable portion of the land is not marked by homogenity of ground cover, a vast amount of the area consists of water and large agricultural fields, areas characterized by homogenity over large areas. Consequently, the areal complexity of most of this area is low.

This area was chosen to be representative of a typical agricultural area in Tuscaloosa County as well as the type of suburban development that would be expected on the urban fringe of Tuscaloosa. The paper mill was included as an example of the industry that is located along the Black Warrior River. Lake Tuscaloosa is representative of many

large impoundments throughout the State while the Black Warrior River typifies many Alabama rivers used for transportation and the location of industry.

6.4 Summary of Study Area Characteristics

By applying the composite sequential clustering technique to these two areas, a variety of the situations discussed in section 6.1 were encountered. Land with both severe and moderate slope was examined. ERTS data affected by clouds was processed. Study area one has very few types of land cover while study area two has many types of land cover. A considerable portion of study area two has very low areal complexity while other parts of study area two and portions of study area one affected by cloud cover and severe slope have higher areal complexity.

The exposed soil in each study area is distinctive since each is in a different geologic region. Study area one is underlain by shale and sandstone with some clay, sand, and gravel on the tops of hills while study area two is underlain by clay, sand, and gravel.

This combination of situations should provide an adequate basis for studying the performance of the CSC technique when applied to ERTS data of Tuscaloosa County.

CHAPTER VII

DISCUSSION OF RESULTS

7.1 Manual Interpretation of Land Use

To adequately evaluate the unsupervised classification, a method for quantifying the comparison of the automatically-derived classes to the existing land use was required. The ERTS-derived categories were simply numbers assigned to acre-sized parcels of land arranged in a grid-like array over the land. Before any quantitative comparison was made, the ground-truth information had to be expressed in the same form.

As discussed in section 1.4, this involved classifying the land into a finite number of land-use categories and producing a ground-truth map. This was done after the classification map was received and examined for the number of classes generated and the patterns they formed.

Several factors were considered in the selection of those categories suitable for comparison. Some categories were included because they seemed to have an effect on the classification. Other categories were included in order to show they were undetectable by the technique. All categories selected had to be easily identified on the air photo coverage.

A grid of ERTS data point locations was fitted to the ground-truth map so comparison would be possible. Each interpreted land-use category was then assigned a number and the data on the ground-truth map was transferred onto computer cards in the form of the dominant land-use category per data point on the grid. The result was a number assigned to each data point, the same form as the ERTS-derived categories.

7.1.1 Interpreted Land Use In Study Area One

The ground-cover in this area was classified into six categories (Figure 11). These six categories were interpreted from an air photo taken April 29, 1973, with a VC-8 camera using Acrochrome color infrared 2443 film which has a spectral response in the range of 0.5 to 0.9 microns. The photograph was at a scale of approximately 1:122,000.

The first category was deciduous and mixed forest. During the spring the deciduous trees were foliated and appeared bright pink on the photograph. Where the deciduous trees were mixed with pine, the pink was somewhat duller but did not present enough contrast for consistent identification. Consequently, deciduous and mixed forest were classed together.

The second category was pine forest. These areas appeared dark on the spring coverage. Although some deciduous trees were present in these areas, the proportion was very low.

The cloud shadows were category three. The cloud shadows (and clouds discussed later) were located by projecting the ERTS image of MSS band six onto the map.

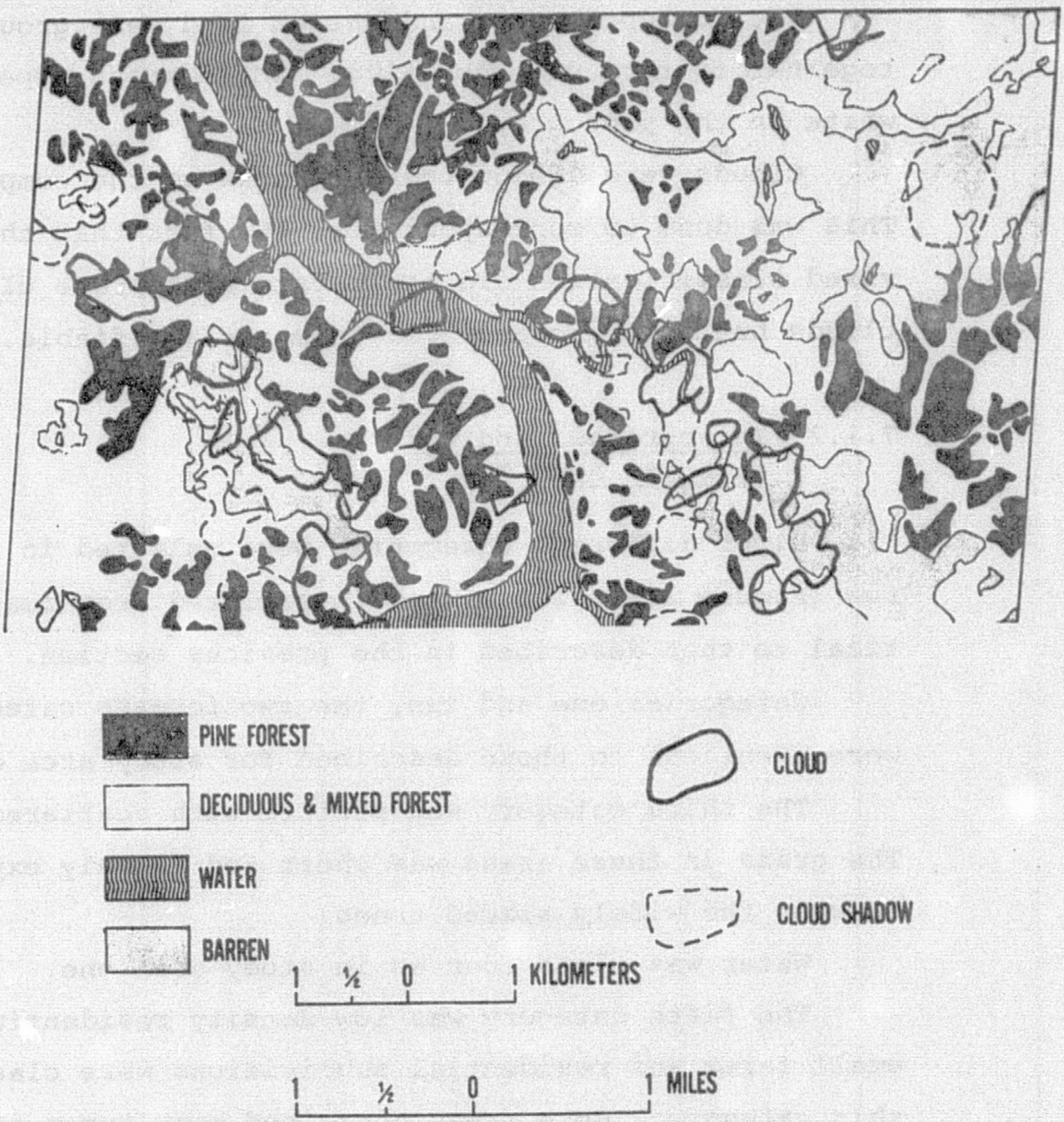


Figure 11. Map of Interpreted Categories for Study Area One

Water in study area one was category number four.

The stripped areas and barren land were grouped together to form category five. These areas appeared white on the photograph.

Clouds were designated as blanks on the computer cards. This was done to correspond with the fact that the unsupervised classification did not create a separate class for clouds but simply considered them unclassifiable.

7.1.2 Interpreted Land Use in Study Area Two

Eight different categories were selected in study area two (Figure 12). These were interpreted from imagery identical to that described in the previous section.

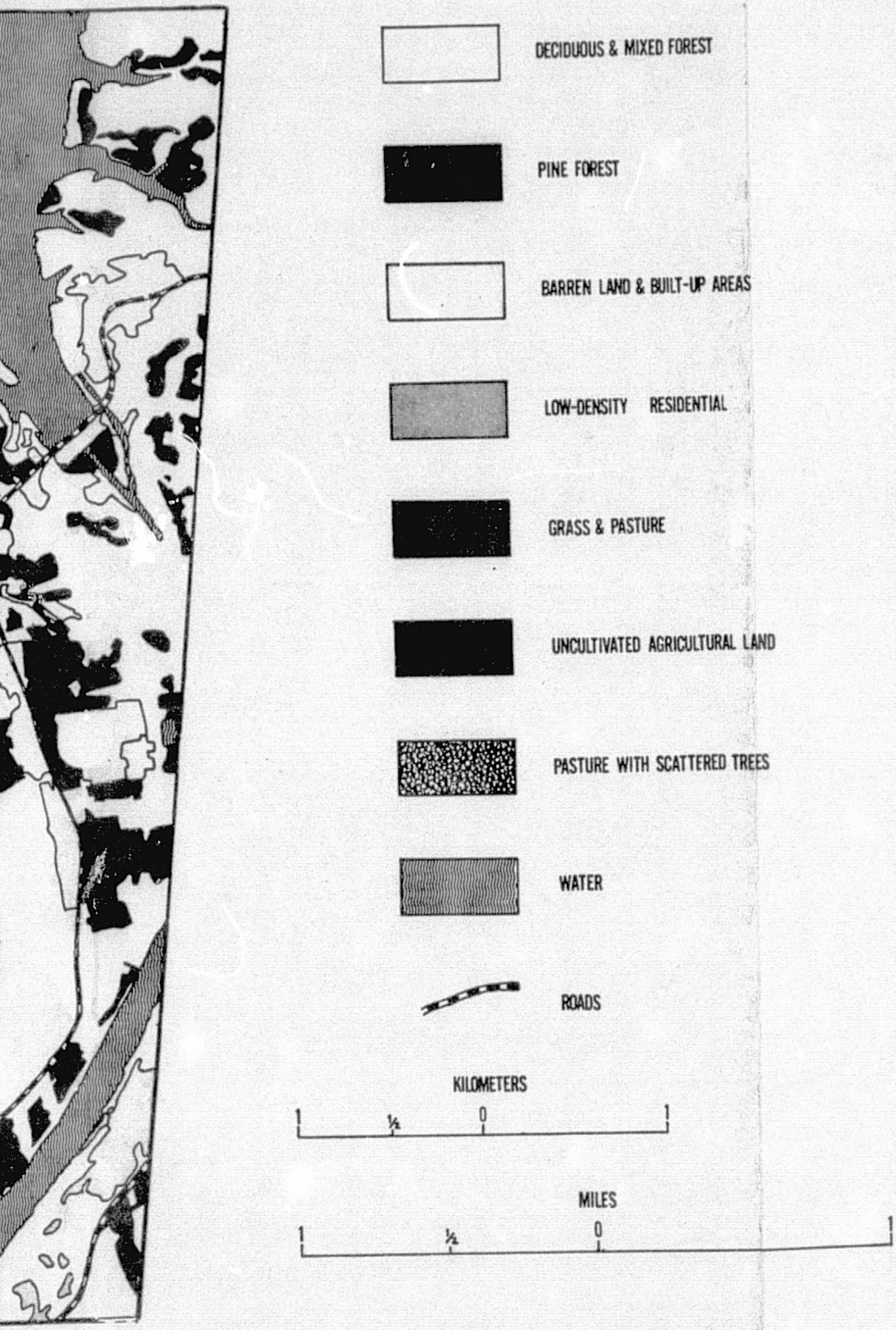
Categories one and two, the two forests categories, were identical to those described for study area one.

The third category was pasture with scattered trees. The grass in these areas was short and largely exposed between the widely spaced trees.

Water was class four as in study area one.

The fifth category was low-density residential. Both small farms and residential subdivisions were classed in this category. Both areas contained many types of ground cover in a small area. Subdivisions were composed of roof tops, cement, asphalt, grass, and trees. Land in small farms consisted of roof tops, grass, trees, barren land, and gardens. Since both were characterized by similar ground-cover combinations and extreme areal complexity, they were classed together.

Figure 12. Map of Interpreted Categories
in Study Area Two



FOLDOUT FRAME 2

Categories six and seven represented open non-forested areas. Class six was grass and pasture land. This was land that supported growth of living grass and appeared a dull pink to a light burgundy color. Generally, these were areas where the grass was short. Class seven was uncultivated agricultural land. This land was covered with the residue from the harvest of the previous Autumn. Subsequent investigation (after the naming of the category) revealed that this category also included unused fields grown up with tall grass and shrubbery which appeared as a gray color on the photography.

Barren land and built-up areas were considered to be category number eight. Barren land included tilled agricultural fields as well as land left bare because of construction. A built-up area was defined as high-density urban land which was completely devoid of vegetation. This included such features as shopping and business areas, roads, a federal housing project, warehouses, and a school. Barren land and built-up areas were classed together since both types of land were unvegetated and appeared to have a high reflectance.

7.2 Automatically-Derived Classes

Several visual and statistical tools facilitated analysis. The classification map itself was one tool when it was produced at the correct scale for comparison. This was done by assigning each class a color and producing a color-coded digital map at the scale of the grid.

The spectral signatures of the classes could be easily compared when the statistical characteristics of the classes

were transcribed into a graphic form (Figures 14 and 16). The units of reflectance on the abscissa range from zero (total absorption) to sixty-four (total reflection). The range of the data within one standard deviation of the mean reflectance in each band is indicated by bars above and below each point.

The automatic comparison of the interpreted categories to the ERTS-derived classes was used in two ways. The characteristics of each ERTS-derived class could be easily studied by noting the percentage of the class that corresponded with each interpreted category (Tables 1 and 6). Similarly, the characteristics of each interpreted category could be evaluated by noting the percentage of the category that corresponded with each ERTS-derived class (Tables 3 and 7).

To aid in understanding the interrelationship of the clusters in multi-dimensional space, the Euclidian distance between each pair cluster centers was calculated (Table 4 & 8). Those cluster centers separated by small distances are more similar than those separated by large distances. This matrix of distances helped in understanding misclassified data points.

The CSC technique generated five classes in each study area. The characteristics of each class in each study area are discussed in the subsequent sections.

7.2.1 Automatically-Derived Classes in Study Area One

The classification map of this study area is shown in figure 13. Classes one and two (green and yellow) are

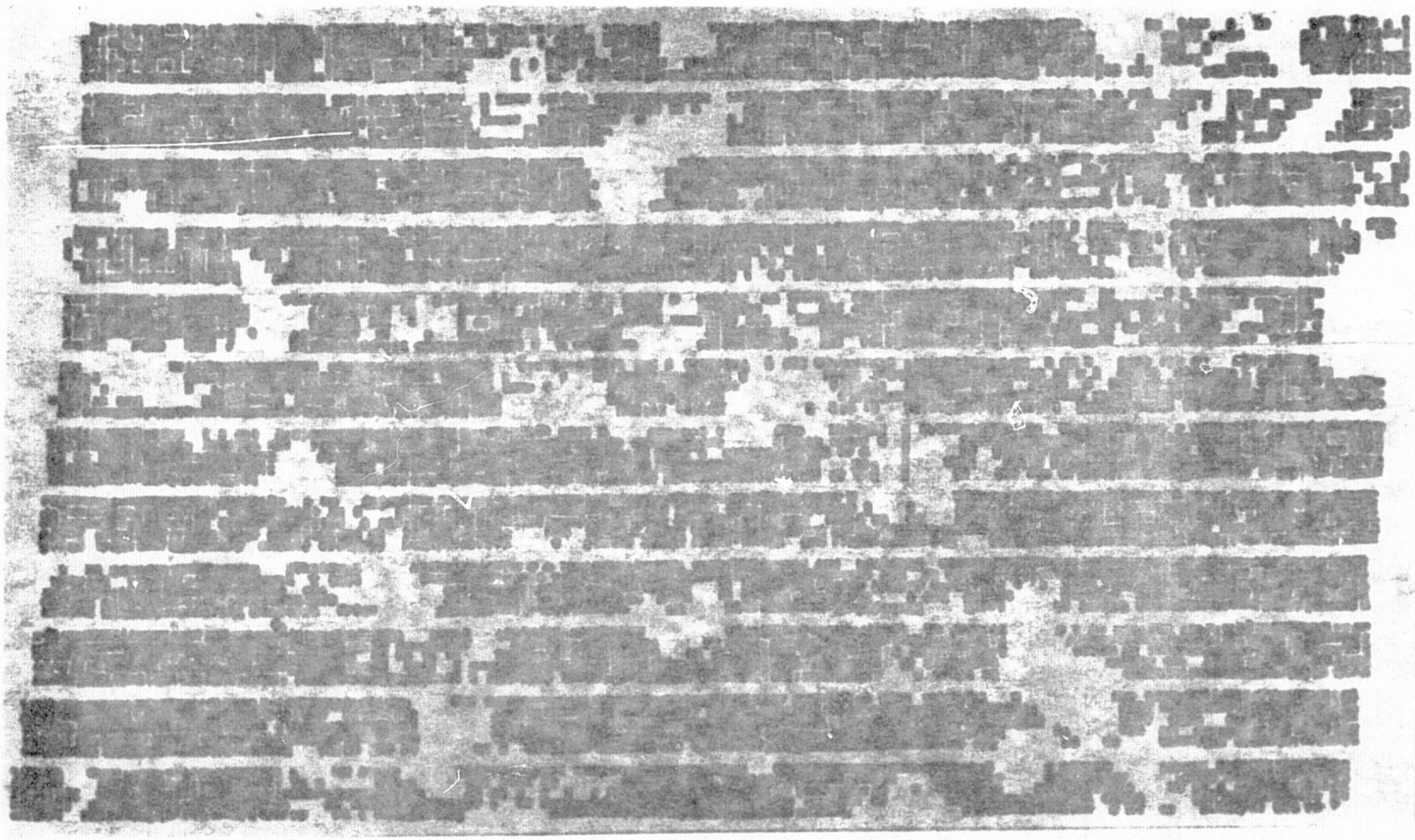


Figure 13. Color-Coded Map of Automatically-Derived Classes for Study Area One

TABLE 1

COMPARISON OF INTERPRETED CATEGORIES AND AUTOMATICALLY-DERIVED CLASSES IN TERMS OF THE PERCENTAGE OF EACH AUTOMATICALLY-DERIVED CLASS FOR STUDY AREA ONE

	Class 1	Class 2	Class 3	Class 4	Class 5	Unclassified
Deciduous & Mixed Forest	67.2 (2072)	46.9 (694)	57.6 (1009)	13.8 (109)	17.4 (156)	15.4 (255)
Pine Forest	27.5 (850)	30.4 (449)	12.8 (224)	1.4 (11)	3.9 (35)	4.7 (77)
Cloud Shadow	0.6 (20)	8.7 (129)	1.1 (21)	34.9 (276)	1.0 (9)	9.3 (154)
Water	0.9 (28)	7.2 (106)	0.4 (7)	44.4 (349)	1.1 (10)	6.6 (109)
Stripped Areas & Barren Land	2.8 (88)	5.4 (80)	23.3 (408)	4.6 (36)	66.9 (600)	26.6 (441)
Clouds	1.0 (30)	1.4 (21)	4.8 (84)	0.9 (7)	9.7 (87)	37.4 (619)
Total	100.0 (3088)	100.0 (1479)	100.0 (1753)	100.0 (788)	100.0 (897)	100.0 (1653)

primarily forest in this classification since almost ninety percent of all areas in these two classes correspond with areas interpreted as either pine or deciduous forest. About seventy percent of class three (orange) also corresponds to areas interpreted as forest (Table 1). It is apparent that the forested areas in study area one are represented by three different classes.

The class into which a section of forest is classified depends on three factors - the slope of the land, the density of the forest, and the type of trees in the forest. An excellent example of the effect slope has on the classification is shown along the banks of the Black Warrior River where the slopes are quite severe. The ERTS pass was made about 9:30 A.M. local time, the same time of day the air photo of the area was taken (Figure 9). Examination of figure nine shows the effect the morning sun angle had on the light striking each bank of the river. The slope on the west bank received the direct rays of the sun while the slope on the east bank faced away from the sun. The classification reflected this difference in illumination. Whereas the characteristics of the forest are the same on both banks of the river (Figure 11), the west bank was classified as three (the higher reflectance) and the east bank was classified as two (the lower reflectance). Reasonably, class one idicates similar forest on moderate slopes since its reflectance is between class two and class three (Table 2 and Figure 14).

The density of the trees and the lushness of the foliage also has a definite effect on the reflectance of the forest. Logging areas, for example, have low tree density and were classed as three. One such area is in the western section

TABLE 2

SPECTRAL CHARACTERISTICS OF AUTOMATICALLY-DERIVED CLASSES FOR STUDY AREA ONE

	Spectral Mean Values				Spectral Standard Deviations			
	MSS Band				MSS Band			
	4	5	6	7	4	5	6	7
Class 1 (green)	28.282	21.929	30.607	16.095	1.266	1.695	2.268	1.436
Class 2 (yellow)	27.640	20.867	23.721	13.892	1.802	2.577	3.684	2.637
Class 3 (orange)	31.810	27.309	32.626	16.485	2.387	3.441	2.768	2.488
Class 4 (blue)	30.320	22.187	15.24	5.513	4.495	4.556	3.015	2.280
Class 5 (purple)	38.319	38.107	37.221	16.455	2.869	3.854	3.629	2.351

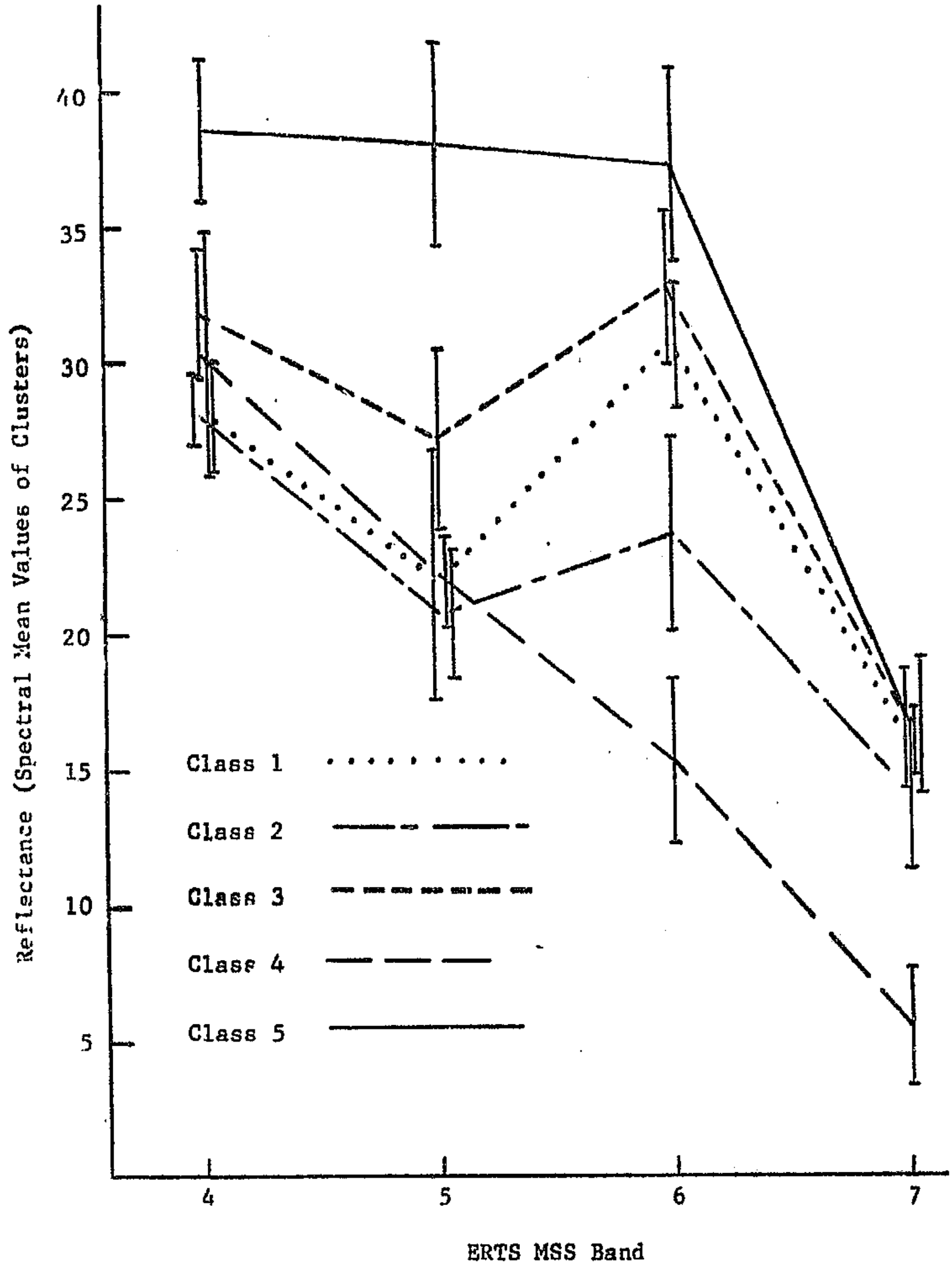


Figure 14. Spectral Signatures of Automatically-Derived Classes in Study Area One

of the study area just west of the large strip mine. The sparse cover within the area is quite evident in figure nine. Examination of the same area on the unsupervised classification (Figure 13) shows the entire area classed as three.

Although the effect of forest type is less evident than the first two factors, examination of table three does reveal the slight effect forest type exert on the classification. The data indicates that areas classified as pine forest tended to have lower reflectance than areas classified as deciduous and mixed forest. Class three, the high reflectance class, contains almost twenty-four percent of the deciduous trees and only about fourteen percent of the pine trees while class two, the low reflectance class, contains only sixteen percent of the deciduous trees and over twenty-seven percent of the pines (Table 3). Evidence seems to indicate that the classification of any resolution element of forest in this study area depended on its slope, the density of the trees, and the type of trees in the forest.

Class three also represents a considerable portion of the stripped areas (25 percent). Examination of air photos showed stripped areas classified as three consisted of spoil banks and strip pits filled with water. The area within a resolution element classed as three was probably some combination of exposed rock, shadow, and water.

About sixty-seven percent of the land classified as five (purple) corresponds with stripped areas and barren land. Stripped areas classed as five tend to be more even than those areas classed as three. Since there were fewer shadows and areas of standing water combined with the rock, the reflectance was higher (Figure 14). The resulting signature is probably that of exposed shale and sandstone.

TABLE 3

COMPARISON OF INTERPRETED CATEGORIES AND AUTOMATICALLY-DERIVED CLASSES IN TERMS OF THE PERCENTAGE OF EACH INTERPRETED CATEGORY FOR STUDY AREA ONE

	Class 1	Class 2	Class 3	Class 4	Class 5	Unclas-sified	Total
Deciduous & Mixed Forest	48.3 (2072)	16.2 (694)	23.5 (1009)	2.5 (109)	3.6 (156)	5.9 (255)	100.0 (4295)
Pine Forest	51.6 (850)	27.3 (449)	13.6 (224)	0.7 (11)	2.1 (35)	4.7 (77)	100.0 (1646)
Cloud Shadow	3.3 (20)	21.2 (129)	3.4 (21)	45.3 (276)	1.5 (9)	25.3 (154)	100.0 (609)
Water	4.6 (28)	17.4 (106)	1.1 (7)	57.4 (349)	1.6 (10)	17.9 (109)	100.0 (609)
Stripped Areas & Barren Land	5.3 (88)	4.8 (80)	24.7 (408)	2.2 (36)	36.3 (600)	26.7 (411)	100.0 (1653)
Clouds	3.5 (30)	2.5 (21)	9.9 (84)	0.8 (7)	10.3 (87)	73.0 (619)	100.0 (848)

About ten percent of class five corresponds with clouds. Examination of the digital map (Figure 13 shows that these class five data points tend to cluster around the edge of clouds which are indicated by large parcels of unclassified points. The location of these points may be where the clouds were especially thin. The light reflected by the land beneath the clouds is obsured from the satellite by the cloud cover. Near the edges, however, the clouds are thin enough to permit passage of the longer wavelengths of light. This light is detected by MSS band seven. Data collected under these conditions records the high reflectance of the clouds in MSS bands four, five, and six, but records the much lower reflectance of the land beneath in MSS band seven. Examination of figure fourteen shows that this approximates the spectral signature of class five. Consequently, it is not surprising that class five data points occur at the edges of the clouds.

Finally, class five cells also indicate the location of the tilled agricultural field in the area. The small cluster of purple in the extreme southwest corner of figure thirteen is the location of this field.

Class four cells (blue) indicate the location of water and cloud shadows in about eighty percent of the cases. Since class four has a very unique spectral signature (Figure 14) and the cluster representing class four is quite distant from the other clusters (Table 4), it would seem that more than eighty percent of the class would be identified with water or cloud shadows. The reason for this is twofold. There was some difficulty in aligning the grid with respect to the Black Warrior River. Consequently, a significant percentage of the class four points corresponded with the

TABLE 4

EUCLIDIAN DISTANCES BETWEEN AUTOMATICALLY-DERIVED CLUSTER CENTERS FOR STUDY AREA ONE

	Class 1 (green)	Class 2 (yellow)	Class 3 (orange)	Class 4 (blue)	Class 5 (purple)
Class 1 (green)	-	7.336	6.752	18.768	20.412
Class 2 (yellow)	7.336	-	12.036	12.288	24.719
Class 3 (orange)	6.752	12.036	-	21.236	13.669
Class 4 (blue)	18.768	12.288	21.236	-	30.470
Class 5 (purple)	20.412	24.719	13.669	30.470	-

forested areas bordering the river. Secondly, many of the resolution elements along the border of the river dominated by water in the manual interpretation are actually composite data points (combinations of water and forest) and were classified into other classes.

Unclassified data points (blank) denote the location of clouds in about thirty-seven percent of the cases. The unclassified points corresponding to clouds are different from other unclassified areas in that they are in contiguous parcels, whereas other unclassified data points are broken up into small areas.

A significant percentage of unclassified points are also found in stripped areas (26.6 percent). The nature of these unclassified points will be discussed in section 7.3.

7.2.2 Automatically-Derived Classes in Study Area Two

As in study area one, the CSC technique generated five classes. The classification map of the area is shown in figure fifteen. Classes one (green), two (orange), and three (yellow) appear to have approximately the same spectral characteristics as the first three classes in study area one (Figures 14 and 16, and Tables 2 and 5). Again the forested areas are identified by either of these classes. Examination of table six shows that classes one and two identify forested areas in about eighty-six percent of the cases and a significant portion of the points classed as three also represent forest (51 percent).

The classification of forest is study area two was determined by two primary factors - the density and height

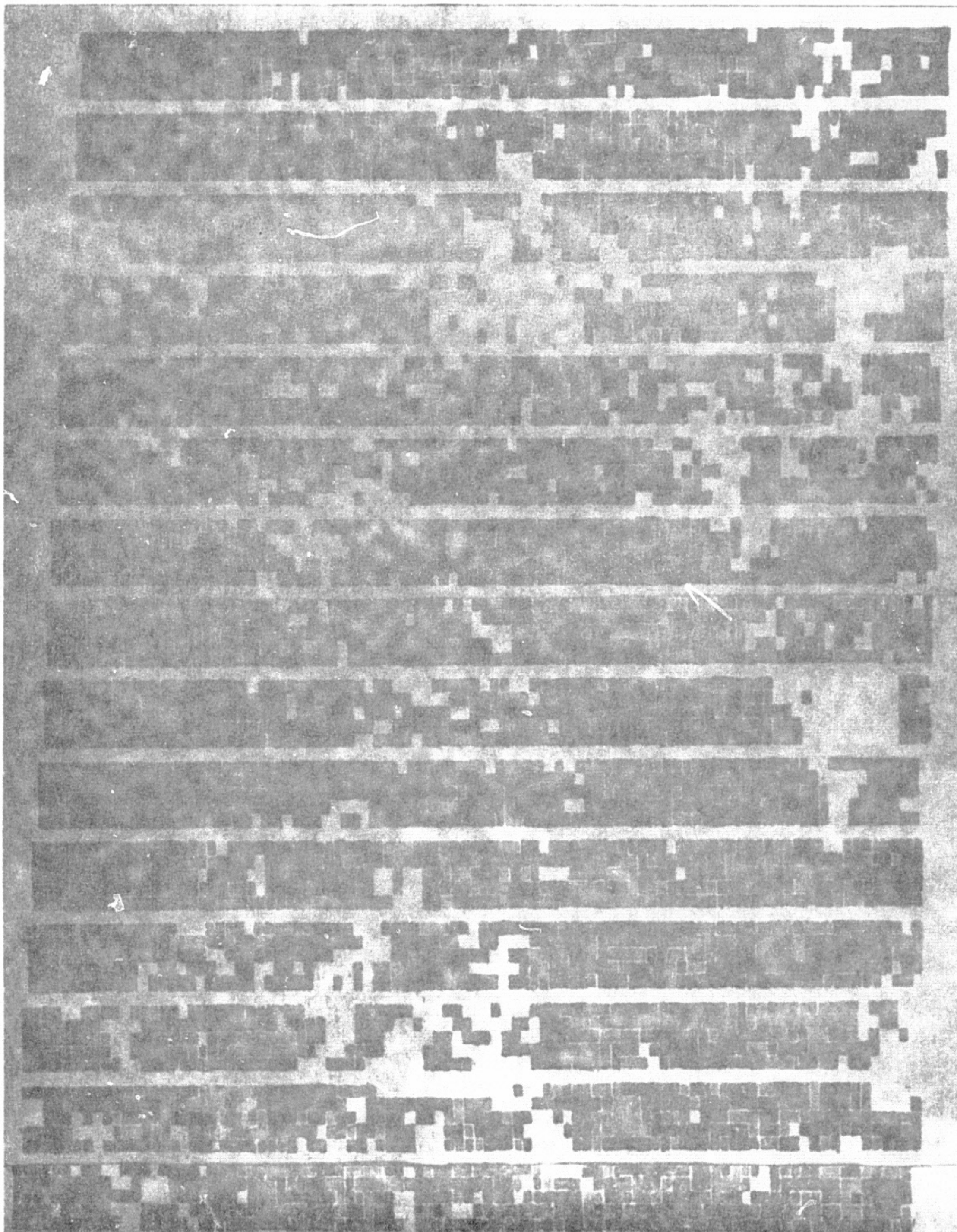


Figure 15. Color-Coded Map of Automatically-Derived Classes for Study Area Two

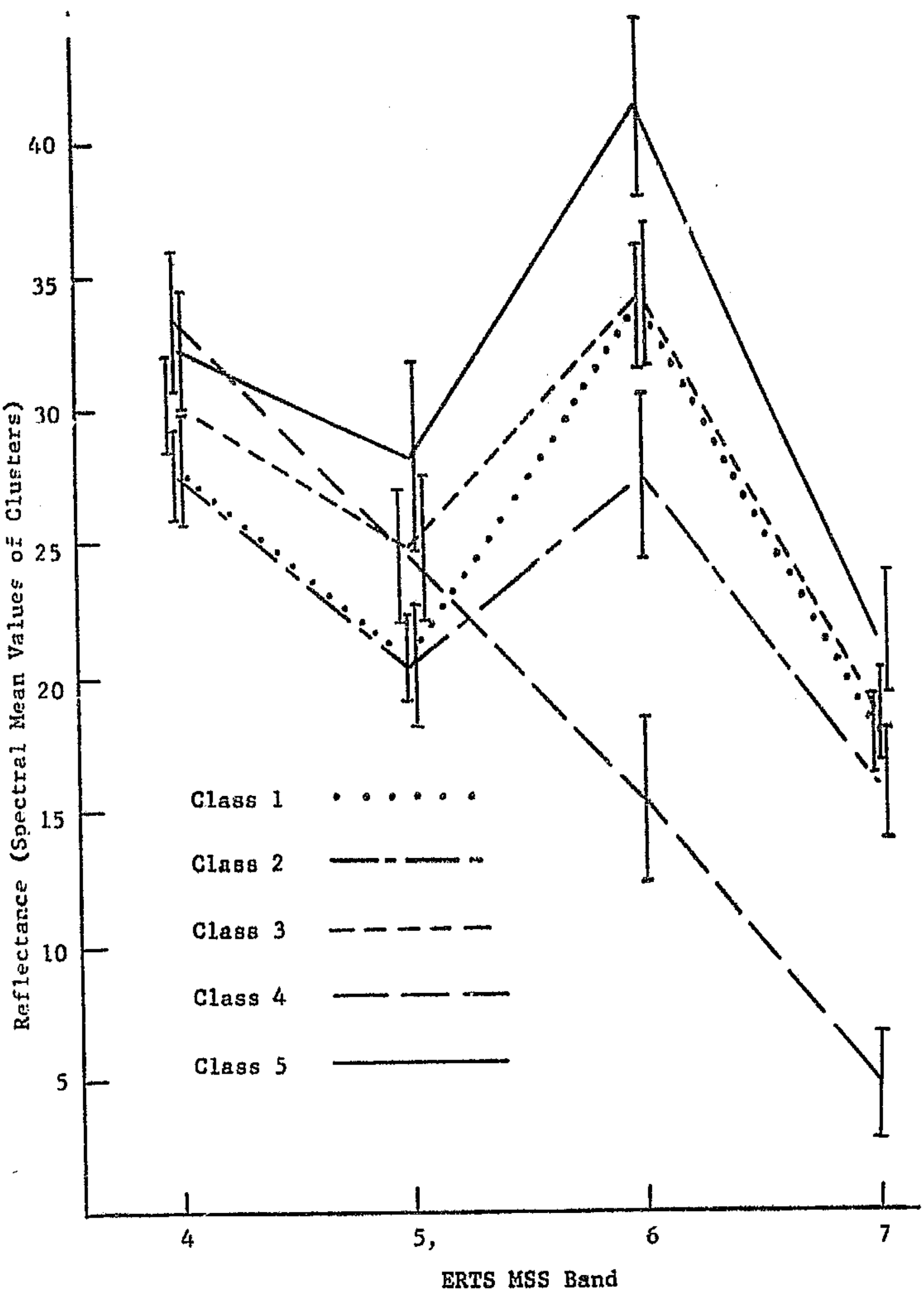


Figure 16. Spectral Signatures of Automatically-Derived Classes in Study Area Two

TABLE 5

SPECTRAL CHARACTERISTICS OF AUTOMATICALLY-DERIVED CLASSES FOR STUDY AREA TWO

	Spectral Mean Values				Spectral Standard Deviations			
	MSS Band				MSS Band			
	4	5	6	7	4	5	6	7
Class 1 (green)	27.787	20.822	33.769	17.820	1.121	1.481	2.411	1.420
Class 2 (orange)	27.634	20.625	27.419	15.972	1.720	2.199	3.008	2.083
Class 3 (yellow)	30.282	24.855	34.014	18.473	1.676	2.650	2.842	1.846
Class 4 (blue)	33.339	24.544	15.313	4.731	2.676	2.413	3.261	2.114
Class 5 (purple)	32.420	28.162	41.263	21.588	2.083	3.734	3.363	2.265

TABLE 6

COMPARISON OF INTERPRETED CATEGORIES AND AUTOMATICALLY-DERIVED CLASSES IN TERMS OF THE PERCENTAGE OF EACH AUTOMATICALLY-DERIVED CLASS FOR STUDY AREA TWO

	Class 1	Class 2	Class 3	Class 4	Class 5	Unclassified
Deciduous & Mixed Forest	66.6 (1117)	63.7 (503)	43.3 (539)	13.1 (35)	11.7 (224)	7.1 (66)
Pine Forest	17.6 (296)	25.6 (202)	7.6 (95)	2.6 (7)	1.5 (28)	2.7 (25)
Pasture with Scattered Trees	1.9 (32)	0.6 (5)	2.4 (30)	0.0 (0)	2.1 (41)	0.5 (5)
Water	0.5 (8)	6.4 (51)	4.3 (54)	83.2 (223)	0.3 (6)	7.0 (65)
Low-Density Residential	1.2 (20)	0.3 (2)	6.0 (75)	0.0 (0)	8.1 (158)	3.9 (36)
Grass & Pasture	5.0 (84)	1.4 (11)	9.6 (120)	0.0 (0)	25.8 (494)	21.5 (199)
Uncultivated Agriculture	3.9 (65)	0.6 (5)	14.4 (178)	0.0 (0)	32.8 (629)	23.9 (221)
Barren Land & Built-Up Areas	3.3 (56)	1.4 (11)	12.4 (153)	1.1 (3)	17.7 (339)	33.4 (309)
Total	100.0 (1678)	100.0 (790)	100.0 (1244)	100.0 (268)	100.0 (1917)	100.0 (926)

of the forest, and the type of trees. The slope of the land did not seem to influence the classification.

There is considerable evidence that the density and height of the forest was the overriding factor in its classification. Large areas classified as two (low reflectance) were found to have significantly higher density and/or significantly taller tree height than surrounding areas classified as one or three. Large forested areas classified as three (high reflectance) were also checked and these areas tended to be sparsely wooded with shorter trees. For example, there is an orchard in the area where the trees are widely spaced at regular intervals. This entire area was classed as three. The interpreted category of "pasture with scattered trees" is another excellent example of a sparsely wooded area. Examination of this class in table seven shows that class three (high reflectance) has a much higher percentage of this category than class two, the low reflectance class (26.4 percent compared to 4.4 percent). Apparently, areas where the tree density is low tended to be classified as three.

The type of forest seemed to be a secondary factor. In this study area as in study area one, pine forest seemed to have a lower reflectance than deciduous and mixed forest. Class three (high reflectance forest) contains almost twenty-two percent of the deciduous trees and only about fifteen percent of the pines while class two (low reflectance forest) contains only twenty percent of the deciduous trees and over thirty percent of the pines.

The type of forest obviously affects the classification to some degree. By examining the condition of the forest during the ERTS pass some explanation for the difference

TABLE 7

COMPARISON OF INTERPRETED CATEGORIES AND AUTOMATICALLY-DERIVED CLASSES IN TERMS OF THE PERCENTAGE OF EACH INTERPRETED CATEGORY FOR STUDY AREA TWO

	Class 1	Class 2	Class 3	Class 4	Class 5	Unclas-sified	Total
Deciduous & Mixed Forest	45.1 (1117)	20.2 (503)	21.7 (539)	1.4 (35)	9.0 (224)	2.6 (66)	100.0 (2484)
Pine Forest	45.3 (296)	30.9 (202)	14.5 (95)	1.0 (7)	4.3 (28)	3.8 (25)	100.0 (653)
Pasture with Scattered Trees	28.4 (32)	4.4 (5)	26.5 (30)	0.0 (0)	36.3 (41)	4.4 (5)	100.0 (113)
Water	2.0 (8)	12.5 (51)	13.3 (54)	54.3 (223)	1.4 (4)	16.0 (65)	100.0 (407)
Low-Density Residential	6.8 (20)	0.7 (2)	26.0 (75)	0.0 (0)	54.0 (156)	12.5 (36)	100.0 (289)
Grass & Pasture	9.3 (84)	1.2 (11)	13.2 (120)	0.0 (0)	54.4 (494)	21.9 (199)	100.0 (908)
Uncultivated Agriculture	5.9 (65)	0.5 (5)	16.2 (178)	0.0 (0)	57.3 (629)	20.1 (221)	100.0 (1098)
Barren Land & Built-Up Areas	6.4 (56)	1.3 (11)	17.6 (153)	0.3 (3)	38.9 (339)	35.5 (309)	100.0 (871)

in reflectance is possible. According to the Alabama Forestry Commission the first leaves appeared on the deciduous trees in early April, after the ERTS pass. However, the leaves on the shrubs and bushes which comprise the underbrush typically appear before there is any foliage on the trees. Consequently, the condition of the forest during the ERTS pass was non-foliated deciduous trees, foliated pine trees, and foliated underbrush.

The broad leaves on the underbrush reflect light well. When deciduous forest were imaged, the underbrush exposed by the barren deciduous trees produced high reflectance readings, but when pine forest were imaged, the pine needles obscured the high reflectance of the underbrush by diffusing the light. Consequently, the pine forest tended to have a lower reflectance than the deciduous and mixed forest.

As in study area one, class three also represented some non-forested categories. A large part of the residential land was classed as three (26 percent). These residential areas are situated in moderately dense forest. Large sections of open fields were also classified as three. High grass and shrubbery were found growing in these areas. Perhaps the most unique characteristic of this class is that data points classed as three are a significant part of every catagory (Table 7). The location of class three points offers one explanation for this. They are found in significant numbers on the borders of forested and non-forested categories. Consequently, one is led to believe that class three often represents a composite of forest and other types of land cover.

Class four data points (blue) correspond to surface water locations about eighty-three percent of the time. As discussed in the previous section and from examination of table eight, the spectral signature of water should make it an easily identified class, yet the results of the automatic classification seem to indicate poor performance in the identification of surface water. There are several reasons for this. The alignment of the Black Warrior River was very poor. An explanation for this could not be found since other features in the area lined up well. In any case, this caused areas interpreted as forest along one bank of the river to align with data points in class four. Along the other side of the river the surface water aligned and with the classes indicating forest. This resulted in an unusually high percentage of resolution elements interpreted as forest to correspond with class four (13.1 percent) and an unusually high percentage of points interpreted as water to correspond with classes one, two, or three (27.8 percent). A second reason for the poor identification of water was the presence of composite data points (combinations of water and forest) which tended to decrease the apparent area of surface water since they were not classed as four.

Class five (purple) was the class with the highest reflectance in this study area. Generally this class was representative of non-forested categories - grass and pasture, uncultivated agricultural land, and barren and built-up areas.

When areas categorized as grass and pasture, or uncultivated agricultural land was classified as five the area was

TABLE 8

EUCLIDIAN DISTANCES BETWEEN AUTOMATICALLY-DERIVED CLUSTER CENTERS FOR STUDY AREA TWO

	Class 1 (green)	Class 2 (orange)	Class 3 (yellow)	Class 4 (blue)	Class 5 (purple)
Class 1 (green)	-	6.618	4.793	23.593	12.070
Class 2 (orange)	6.618	-	8.640	17.911	17.403
Class 3 (yellow)	4.793	8.640	-	23.410	8.817
Class 4 (blue)	23.593	17.911	23.410	-	31.168
Class 5 (purple)	12.070	17.403	8.817	31.168	-

covered with short grass or the residues from the harvest of the previous autumn. Class five was also the principle indicator of the category denoting barren land and built-up areas.

A significant percentage of the pasture with scattered trees category and the low-density residential category was classed as five. When pasture with scattered trees was classed as five it was in an area where the trees were unusually sparse. When low-density residential areas were classed as five, the subdivision was in an area of very few trees.

An unusually large percentage of class five corresponds with forested areas (13 percent). The reason for this is obvious when one considers that class five is the larges single automatically-derived class and the two forest categories comprise almost half of the study area. Since each covers so much area, any slight misalignment of the grid of data point locations would cause many forested areas and areas classified as five to correspond.

Unclassified data points were not indicative of any particular category. In fact, unclassified data points comprise a significant portion of every non-forested category. The reason for this is discussed in the subsequent section.

7.3 Unclassified Data

The unclassified data in each study area appears to be the major problem in the application of the CSC technique to ERTS data. The initial assessment concerning the nature of unclassified data prior to analysis of the results was that composite data points would produce "freak" spectral signatures and be left unclassified. One category indicative of extreme diversity within limited areas and consequently containing a high percentage of composite data points is the

low-density residential category. Yet, this category's percentage of unclassified points was about average (Table 6).

Unclassified data points seem to be most common in water, which is represented by class four, and in high reflectance areas, which tend to be represented by class five and sometime class three. One reason for this can be seen by examining the spectral signatures of class four and five in each study area, and then noticing the distance of these two classes from the other clusters in tables four and eight. Both are quite a distance from each other and from clusters one, two, and three. Since all data points beyond three standard deviations from any cluster center are left unclassified, points in the region of clusters one, two, and three would be more likely to fall within the required distance of some cluster center compared to points with high reflectance or points in the region of cluster number four.

Another explanation for the unclassified data is the presence of "bad" data caused by "banding" in the data. This data is used along with the "good" data in the establishing of classes and in the improvement of the cluster center locations. Since the accuracy of this data is extremely doubtful, it alters the locations of the cluster centers and the values of the standard deviation vectors. This slight alteration in the location of the cluster centers and the decision hyperplanes has the effect of leaving otherwise "good" data unclassified and changing the classification of other data.

Perhaps the best explanation for the unclassified data is that the first step of the CSC technique does not establish enough initial cluster centers. This explanation is

quite feasible when one notes that most of the unclassified data corresponds with water and high reflectance categories. Since very few cluster centers were established in the portions of multi-dimensional space used to classify these categories, it is not surprising that many data points in these areas are not within three standard deviations of a cluster center and are left unclassified.

Whatever the reasons for the existance of unclassified data and the limited number of classes generated by the technique, these remain as the primary problems to be addressed in the application of the CSC technique to ERTS data. The following chapter summarizes the performance of the CSC technique, proposes several modifications to the technique, and projects its practical applications.

CHAPTER VIII

SUMMARY AND CONCLUSIONS

8.1 Summary

The unsupervised classification analyzed in this study showed encouraging results despite several factors which tended to handicap the technique's performance. One factor which tended to handicap the performance of the CSC technique was the nature of the areas analyzed. Instead of restricting analysis to strictly agricultural areas or strictly urban areas they were combined into one study area. The results showed this to be a handicap since low-density residential land had similar signatures to some agricultural areas. In addition the study areas were not ideal for obtaining high classification accuracies. The ideal situation for any automatic classification technique is land composed of large areas of homogeneous ground cover. The results showed large areas of one classificaiion to be the exception rather than the rule, so apparently the areas chosen for analysis are quite variable in their spectral response. In very rugged portions of the study areas the slope of the land caused the spectral response to vary. In other areas the high areal complexity of the land and the lack of homogenity within interpreted categories caused variability in the spectral response.

The presence of clouds also affected the classification. In study area one class four identified two different categories since cloud shadow locations were classed with water. Similarly, class five represented more than one situation since the borders of clouds were classed with high reflectance areas.

As mentioned in the previous chapter, the inaccurate data caused by "banding" effected the classification. The exact effect could not be studied since the spectral values of the inaccurate data were not availible for comparison with the good data. It can be asserted, however, that the "bad" data has very little effect on the establishment of initial cluster centers since very few data points are analyzed at a time in this part of the technique. The "bad" data does influence the improvement of the cluster centers since all the data is used in determining their locations. The distribution of the "bad" data in multi-dimensional space determines how the location of the cluster centers is influenced and how the data is classified. Apparently the distribution of the "bad" data was about the same in each study area since the resulting cluster center locations and classification characteristics are similar.

Finally, it must be considered that the greatest variety of spectral response would probably occur at some time of year other than early spring. At this time of year there are no crops in the fields, only the residues from the last harvest. Consequently, the variation in crop type which would be a factor in the classification of summer ERTS data did not influence this classification and thus fewer classes were formed.

The choice of dates was not ideal for other reasons. The ERTS pass was made during planting season when some fields were tilled and others were not. This was also during the change of seasons when some plants and trees were foliated and other were bare. These variables in the ground-cover characteristics introduced needless uncertainty and could have been eliminated by selection of another date.

One of the main questions addressed in this study was the feasibility of applying unsupervised techniques on a regional scale where all types of land use would be encountered. In this regard, the CSC technique seems applicable. Although the two study areas had completely different characteristics, the spectral classes generated were quite compatible in terms of their spectral signatures. The signatures of classes one through four were almost identical. Class five was not compatible. Class five in study area one represented the exposed sandstone and shale of the strip mines and class five in study area two represented barren soil, built-up areas, and grass. Consequently, the application of the unsupervised technique to the entire county would probably result in six classes being formed.

8.2 Applications

In its present form the technique is very effective in identifying high to medium density forest. With only slight alterations, the technique could be very effective in the identification of surface water, certain types of strip mines, and agricultural fields. The usefulness of the technique after major alterations are made is pure speculation at this point.

Areas classified as one and two in the unsupervised classification of this type of ERTS data will usually be forest of high to medium density and tall to moderate height. By examining those areas classed as one, moderate slopes would be expected and deciduous trees would predominate. Those areas classed as two would have the highest proportion of pine trees and the greatest density of trees with taller heights. By using this method rather than examining the entire forest, many areas of low density, short tree height, and severe slope could be avoided. This application is beyond the capability of small scale air photo interpretation.

If the large percentage of unclassified data points in the classification of surface water could be reduced from the current level of approximately seventeen percent, then the method could be quite effective in the location of surface water.

The problem of unclassified data points is shared by class five in study area one. This class isolates those stripped areas unaffected by drastic slopes and standing water quite well except for the gaps left by unclassified areas.

In study area two, class five can effectively isolate fields, pastures, some types of low-density residential areas, and some barren land and built-up areas. If the area to be analyzed was rural (thus removing urban land from the classification) class five could locate agricultural fields and pastures. Again, a considerable portion of each field would be left unclassified.

One possible solution to the problem of unclassified data in classes four and five would be to "smooth over" the

data for large water bodies, stripped areas, and fields to form solid areas of one classification. If an unclassified data point is flanked by data points of the same classification it is reasonable to assume that the unidentified point is the same classification. By implementing an algorithm to classify unclassified data points by this criterion, the classification accuracy for classes four and five could be enhanced to a more acceptable level.

Although the technique shows promise in the classification of forest, water, stripped areas, and agricultural land, it appears unsuitable for the classification of urban land when when this type of ERTS data is used. Instead of being classified into a unique class, urban areas were represented by either of two classes or they were left unclassified. Researchers at the Johnson Space Flight Center who studied the application of an unsupervised technique to an urban area in Houston, Texas concluded that their clustering techniques did not permit consistent automatic classification of multispectral scanner data into categories according to usual urban land-use terminology. Those clusters which could be related to some pattern in the characteristics of the urban land were not consistent even over the study area under analysis.[25]

The technique also appears unable to detect the differences in water quality that exist within the study areas. All of the surface water in study area two was classed as four or was undetected as a unique class. Even the highly discolored water in the strip pits was not detected as a unique class. Therefore, the application of the CSC technique to ERTS data seems limited to the detection of surface water in general.

The technique's application in the classification of different types of fields and pastures could not be evaluated since no crops were planted. This type of insight will be availible as ERTS data gathered during other seasons is processed by the CSC technique and evaluated.

8.3 Modification of CSC Technique

One of the primary things that hinders the performance of the CSC technique is the limited number of classes that are generated. This may be due to the quality of the ERTS data or some characteristic of the technique. The quality of the ERTS data may be improved by selecting ERTS data from other seasons or by selecting data not effected by "banding." The CSC technique may be improved by finding a better way to establish initial cluster centers.

The limited number of classes produced by the CSC technique has been recognized as a problem for quite some time.[23] Apparently, the first part of the technique is not sensitive enough to detect all of the clusters that actually exist. Consequently, a new method has been proposed by Charles Dalton which will be more sensitive in the selection of initial cluster centers.[26]

8.4 Conclusions

The application of the CSC technique to ERTS data of portions of Tuscaloosa County showed that the delineation of several types of ground cover was possible. Areas whose interpretation depends primarily on texture and shape such

as urban areas could not be identified while areas whose interpretation depends on the density of the foliation were delineated even better than is possible from conventional air photo interpretation.

The spectral classes generated by the CSC technique do not conform to interpreted land-use categories well enough to permit the inventorying of land use in an area. Too few classes were formed and many of the classes that were formed corresponded to several land-use categories. Similarly, many of the interpreted land-use categories were well divided between the ERTS-derived categories. This situation can be improved by the generation of more spectral classes (section 8.3) and redefining new interpreted land-use categories to correspond more closely with the area's spectral response.

Additional research is needed in several areas. ERTS data gathered during other seasons of the year must be processed and evaluated so changes in classification can be noted. Perhaps the different reflectance caused by changes in foliation will result in better recognition of various types of ground cover.

The problem of "banding" must be addressed. The best solution appears to be elimination of the "bad" data from the classification. Although this has been proposed, at this writing no program has been created to detect the "bad" data and eliminate it.

Research is also needed concerning the effectiveness of the new method of establishing initial cluster centers proposed by Mr. Dalton. Although it will be a part of the CSC technique eventually, at this writing it has not been implemented into the computer program. When it is implemented, its performance must be tested and compared.

Comprehensive research of the same nature as this study is absolutely necessary to an adequate understanding of the nature of unsupervised techniques as they apply to ERTS multispectral data. As research is completed in the areas outlined in the previous paragraphs, the CSC technique can become an effective tool in the manipulation of ERTS data for deriving meaningful and timely land-use information.

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THE DETECTION OF BURNING COAL SPOIL EMBANKMENTS BY REMOTELY SENSED TECHNIQUES

Darry A. Ferguson

SECTION TEN

of

VOLUME TWO

- INVESTIGATIONS USING DATA IN

ALABAMA FROM ERTS-A

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NOMENCLATURE

A	=	accelerators
a	=	thermal diffusivity in ft^2/hr
C	=	specific heat in Btu/lb°F
Cm	=	carbonaceous material
Hr	=	heat retention
MCT	=	maximum crossover temperature
Oi	=	oxygen inflow
Q	=	heat released in Btu
R	=	density in lb/ft^3
r	=	radius in ft
t	=	time
Y	=	temperature change in °F
$\Delta\alpha$	=	normal temperature rise
$\Delta\lambda$	=	temperature rise above MCT
π	=	3.14159265

CHAPTER I

INTRODUCTION

1.1 The Problem

For years the coal industry has been disposing of coal waste (called spoil, chitter, refuse or culm) by means of dumps or embankments, usually located in a nearby valley, gully or swamp. As these embankments have grown through the years, they have become subject to fires. The problem of fires or "hot spots" has been intensified by the use of modern mining equipment and methods which enable mining companies to extract coal from thinner seams, consequently more rock is removed from underground and deposited on the refuse pile. In addition, during the separation processes, more carbonaceous material is discarded to the spoil pile. Coupled with the additional combustible material deposited in the dump, the proper amounts of available air and carbonaceous material in the rock, conditions are favorable for combustion whether it be spontaneous or ignited. Remote sensing techniques appear to be very favorable for fast, inexpensive surveillance of burning spoil embankments. This study utilized airborne and surface sensing instruments to survey thirteen embankments in the Warrior and Cahaba coal fields of West Central Alabama. It was the purpose of this study to survey these spoil embankments by remotely-sensed means and to accurately identify any fires or hot spots associated with the spoil pile.

1.2 Scope of Report

Remotely-sensed data may be a product of one or more sources and systems which may be sonic, electrical, magnetic, nuclear radiation or electromagnetic radiation. The remotely-sensed data in this study were derived from the electromagnetic radiation source. During the investigation five distinct systems were evaluated for their usefulness in the detection of coal spoil embankment fires. These were 1) low altitude black-and-white photography, 2) Earth Resources Technology Satellite photography, 3) high altitude infrared photography, 4) hand-held thermal infrared scanning and 5) RS-14 thermal infrared scanning. In this study each system was analyzed using all thirteen spoil piles even though only one complete analysis is presented in the body of this study. The complete list of data is in the Appendix.

1.3 History

Historically residents of coal mining regions have been plagued with smoke, smog, and noxious fumes from coal embankment fires and hot spots, dating back to the early coal mining days in England. Some authorities indicate that these fires may burn for as long as 50 years, creating problems of health and welfare, and resulting in death, injury, and damage whether directly or indirectly related to these fires.[1] There have been numerous accounts of accidents involving workmen and children, some of which are listed in Table 1 prepared by the U. S. Bureau of Mines for an environmental study. Even though a fire may not be readily noticeable, the neighborhood of the coal spoil embankment should recognize the symptoms. The symptoms could be an actual fire,

TABLE 1

PARTIAL LIST OF DEATHS AND ACCIDENTS ATTRIBUTED TO COAL WASTE FIRES

Location	
Iowa	An explosion during excavation of coal waste bank burned 6 men, 3 fatally.
Iowa	An explosion during excavation of coal waste bank burned 11 men, 3 fatally.
Sagamore, W. Va.	Thirteen killed by explosion of a burning coal refuse pile.
Lockgelly, W. Va.	One killed by a slide while digging refuse.
Oakwood, Va.	Seven killed by an explosion and subsequent slide of a bank.
Virginia	Burning refuse bank ignited coal seam. Two killed by explosion while investigating the extent of the fire.
Alabama	Two killed while excavating burning refuse material.
Mayberry, W. Va.	One child killed by falling through surface crust on a burning coal refuse pile.
Oakwood, W. Va.	Two killed by explosion while digging refuse.
Sharples, W. Va.	Burning coal slide covered mine opening, all men rescued 48 hours later.
Hemp Hill, Ky.	Two killed by asphyxiation after falling into a burning bank.
Rhoda, Va.	Two killed by bank slide.
Amherstdale, W. Va.	Explosion and subsequent bank slide injured one child and destroyed several homes.

(McNay 2)

smoke, a noxious odor, or steam rising from the pile after a rain or a combination of all of these.

Residents of Alabama have been annoyed by spoil embankment fires in the recent two decades, although not as much as the residents of West Virginia, Pennsylvania, Kentucky, and other coal mining states. In 1963 the United States Bureau of Mines recorded 495 burning refuse banks in fifteen states, eleven of which were in Alabama (Table 2). This number can be compared to the 282 fires identified by the Bureau of Mines in 1968 (Table 3), with six of these fires in Alabama.

A comparison of the embankments burning in 1963, 1968, and those found burning in 1973 by the writer are presented in Table 4.

1.4 The Origin of Coal Refuse Fires

Spontaneous combustion is the most common cause of coal spoil embankment fires. Some sixty-six percent of the 292 refuse banks found burning in 1968 were believed to have been started by spontaneous combustion.[2] Spontaneous combustion can occur when there is sufficient air entering the dump for oxidation to occur and an insufficient quantity of air to disperse the heat generated by the oxidation of the combustible material, thus allowing the heat to accumulate. (The actual processes that occur during oxidation will be discussed in Chapter II). The ignition of bituminous refuse has been determined to be a function of airflow and particle size variation.

> "Laboratory trials showed that about six times more air passed through the 3 1/2 x 1/4 inch than through the minus 3 1/2 inch refuse for a given pressure differential. About four times more air passed through the minus 3 1/2 inch than through the minus 1/4 inch refuse. The fine refuse appreciably reduced the flow of air.

TABLE 2

BURNING REFUSE BANKS IN 1963

State	Number of Fires
West Virginia	213
Pennsylvania (bituminous)	117
Kentucky	49
Virginia	27
Pennsylvania (anthracite)	25
Illinois	14
Ohio	13
Alabama	11
Colorado	8
Tennessee	5
Utah	4
Indiana	2
Montana	2
New Mexico	2
Wyoming	2
Alaska	1
TOTAL	495

(Stahl 2)

TABLE 3

BURNING REFUSE BANKS IN 1968

State	Number of Fires
West Virginia	132
Pennsylvania (bituminous)	48
Kentucky	27
Virginia	17
Pennsylvania (anthracite)	16
Colorado	15
Alabama	6
Ohio	6
Illinois	4
Utah	4
Montana	3
Maryland	2
Oklahoma	1
Washington	1
TOTAL	282

(McNay 3)

TABLE 4

BURNING COAL REFUSE BANKS IN ALABAMA

No.	1963 Nearest Town	Dist.(mi)	1968 Nearest Town	Dist.(mi)	1973 Nearest Town	Dist.(mi)
1	Maben	0.7	Pleasant Grove	0.0	Parrish	3.0
2	Graysville	5.0	Edgewater	9.0	Graysville #1	5.0
3	Quinton	8.0	Edgewater	9.0	Graysville #2	5.0
4	Quinton	8.0	Edgewater	11.0	Maxine	1.0
5	Praco	0.0	Graysville	4.8	Pleasant Grove	0.5
6	Labuco	0.0	Sayre	1.0	Johns	2.0
7	Dolomite	0.5			West Blocton	1.5
8	Sayre	1.5				
9	Sayre	1.0				
10	America	0.7				
11	Flatcreek	0.0				

(Stahl 2 and McNay 3)

. . . .

The spontaneous ignition tendency of mine refuse was determined by heating the bottom layer of the material contained in a chamber and observing the temperature rise at various levels. The data showed decreasing ignition tendency for minus 3 1/2 inch, 3 1/2 x 1/4 inch, and minus 1/4 inch material. The minus 3 1/2 inch refuse showing signs of activity when the material at the base was heated to 250°F.... The results of three trials with minus 1/4 inch refuse containing 1, 5 and 11 percent moisture indicated that this material under that condition had little tendency toward spontaneous combustion..."[3]

Coal refuse fires have also been a result of burning trash on dumps or even by other burning dumps nearby. Other fires were known to have been started by humans, whether intentional or accidentally, and by forest fires or lightning. Some coal spoil piles are intentionally ignited to produce "red dog," an oxidized shale often used for road base and other industrial uses.

1.5 The Control and Arrest of a Spoil Fire

Several control techniques, most of which have had limited success, have been used to arrest coal embankment fires. These general techniques and their success are discussed in the following paragraphs.

Flooding: Some embankment fires have been extinguished by flooding the hot zone with water. However, flooding has proved to be only temporary in arresting the fire. Once the flow of water is stopped, the temperature rises and fires rekindle. The disadvantages of flooding are the channeling and erosion within the bank that may tend to propagate the fire once the flooding has been stopped. In addition, flooding is hazardous, frequently resulting in explosions.

Slurrying: Limestone slurries have been successful in extinguishing fires, although this procedure is very expensive. The slurry is pumped into boreholes spaced throughout the bank. The limestone is decomposed by the heat to form carbon dioxide, which combines with the water in the slurry to reduce the temperature below the ignition point.

Spraying: In some cases spraying has been very effective in controlling embankment fires. A fine spray is continually sprayed on the bank and allowed to percolate through the bank until the hot spot is cooled. This method is superior to flooding primarily because it does not encourage erosion or channeling within the pile. However, spraying must be continued for a long period of time to control the fire, and when spraying is terminated the fire may rekindle.

Blanketing: The use of limestone, slag, sand, shale and other inert materials to cover the bank has had some success in arresting a spoil fire. However, it is generally difficult to maintain a continuous cover on the burning spot. Even if the cover is effective during the active life of the dump, many times weathering will erode the sealing cover and the burning will again erupt.[2] Experience has indicated that the seal is rendered ineffective if:

1) Normal weathering erodes the seal readmitting air to rekindle the hot, carbonaceous material.

2) The seal is washed away by water falling upon or adjacent to the bank.

3) The internal temperatures of the bank bake the seal, causing it to crack, and allowing air to re-enter.

4) The heat below the seal is sufficient to convert part of the refuse to an ash product that occupies less space. The surface may then slump as a result of gravity or cave in when walked on by a person or an animal.

Isolating: Some fires have been extinguished by isolating and/or removing the hot material. The Bureau of Mines has conducted several tests to determine economical methods of isolating refuse. A series of high-pressure water cannons was used to dislodge the hot refuse. The loose material was then hydraulically transported from the site. This placer mining approach was unsuccessful because of the angularity of the material, loss of hydraulic force away from the cannons and the infiltration of the water into the bank. The test was modified to use bulldozers to move the dislodged hot material at the rate of 40 cubic yards per hour. The cost of water quenching and bulldozer haulage was $0.66 per cubic yard. Another method sprinkled and cooled the spot and then moved the material to an adjacent stripmine. Heavy equipment moved 800 cubic yards per hour and the estimated cost was $0.44 per cubic yard.[3]

Compacting and Sealing: A combination of compacting and sealing may be the best method to arrest a fire. The bank may be packed with large rollers and covered with inert materials placed in layers over the burning area.

It has been found that none of the above methods are consistently reliable in arresting a coal spoil embankment fire. It is believed by the writer that the best method to control such fires is a program of preventive maintenance while the dump is being built. Once the dump

has been abandoned, there is little one can do to control spoil fires without excessive control and maintenance costs.

1.6 Environmental Effects of Burning Coal Spoil Embankments

Coal refuse disposal dumps have been burning and creating environmental problems since coal mining began. The pollution problems of the environment have been generally ignored by industry and area citizens until the past few years. These spoil fires should have attracted more attention earlier since, in addition to air pollution, they have been the cause of a number of deaths.

Approximately 60 million tons of coal were produced in Alabama in the years 1971-1973. During this same period some 30-40 million tons of refuse were brought to the surface and placed on spoil piles. In addition, it is estimated that in the next ten years some 200-250 million tons of refuse will be added to the already large spoil piles. Without proper design and maintenance, many of these spoil embankments may be ignited and cause serious environmental hazards.

It is generally accepted that all coals undergo spontaneous combustion with the exception of possibly anthracite. The spontaneous combustion that occurs in anthracite refuse piles is probably caused by the pyritic material, slate, shale, and extraneous material in the spoil pile. This is emphasized by the high ignition temperature (925^{o}) of anthracite.[4]

Burning coal spoil embankments emit oxides of sulfur which are formed by the decay and oxidation of pyrites in the refuse. Some oxidation of sulfur equations are listed below.

$$FeS_2 + 3O_2 \longrightarrow FeSO_4 + SO_2$$

$$2FeS_2 + 2H_2O + 7O_2 \longrightarrow 2FeSO_4 + 2H_2SO_4$$

In addition, hydrogen sulfide may be formed in a burning pile. The two possible reactions are as follows:

1) The reaction of sulfuric acid and pyritic material in the spoil:

$$H_2SO_4 + FeS \longrightarrow FeSO_4 + H_2O \quad .$$

2) In hot spots carbon may react with sulfur dioxide to form carbon disulfide. The CS_2 would then hydrolize to form H_2S:

$$C + 2SO_2 + 8H^+ \longrightarrow CS_2 + 4H_2O \quad ,$$

$$CS_2 + 2H_2O \longrightarrow 2H_2S + CO_2 \quad .$$

The burning refuse pile emits other gases associated with the combustion of coal. For example, small crystals of sulfur may occur on the surface of the dump which may be formed after the thermal breakdown of FeS_2 on the reaction of hydrogen sulfide with sulfur dioxide:

$$2H_2S + SO_2 \longrightarrow 2S + 2S + 2H_2O \quad .$$[4]

Other gases which are emitted are carbon monoxide, carbon dioxide, methane, and nitrogen oxides. Table 5 gives the specific gravity, the maximum allowable concentration, and the fatal percentage for the common gases around burning spoil embankments.

TABLE 5

FATAL POINT PERCENTAGES OF
BURNING REFUSE GASES

Gas	Sp. Gr.	Max. Allow. Conc., %	Fatal Point %
CO_2	1.5291	0.5	18
CO	0.9672	0.01	0.03 (12-74% Explos.)
H_2S	1.1912	0.002	0.1 (4-46% Explos.)
SO_2	2.2636	0.0005	0.1
CH_4	0.5545	1.0	(5-15% Explos.)
NO_2	1.5895	0.0005	0.005

(Hartman 5)

The Bureau of Mines has assembled data on the effects of sulfur dioxide and particulate pollution on the environment. Naturally the primary emphasis is placed on health. Increased daily death rate occurs at concentrations of 715 $\mu g/m^3$ (0.25 ppm) and higher of sulfur dioxide, over a 24-hour mean and accompanied with smoke at a concentration of 750 $\mu g/m^3$. At concentrations of 500 $\mu g/m^3$ (0.11-0.19 ppm) of sulfur dioxide (24-hour mean), and low particulate levels, older persons with respiratory problems will have breathing difficulties. Also, at concentrations of 600 $\mu g/m^3$ (0.21 ppm) and greater of sulfur dioxide, 24-hour mean, chronic lung disease patients may experience accentuations of symptoms.[3]

Particulate matter combined with certain smoke factors affect visibility and direct sunlight. At concentrations ranging from 100 $\mu g/m^3$ to 150 $\mu g/m^3$ for particulates, coupled with large smoke turbidity factors, the direct sunlight may be reduced up to one-third in summer and two-thirds in winter. At concentrations of 285 $\mu g/m^3$ (0.10 ppm) of sulfur dioxide, accompanied by a comparable concentration of particulate matter and a relative humidity of 50 percent visibility, may be reduced to five miles.

High levels of sulfur dioxide may also increase the corrosion rate on steel as much as 50 percent. At concentrations from 60 $\mu g/m^3$ to 180 $\mu g/m^3$ (the annual geometric mean) for particulates in the presence of sulfur dioxide and moisture, corrosion of steel, and zinc panels occurs at an accelerated rate. In addition, at concentrations of 85 $\mu g/m^3$ and greater of sulfur dioxide (annual mean), chronic plant and vegetable injury and excessive leaf drop may occur. After short exposures (e.g., 4 hours) of about 145 $\mu g/m^3$ to 715 $\mu g/m^3$ sulfur

dioxide may react with either ozone or nitrogen oxides to produce moderate to severe injury to sensitive plants.[3]

A complete study for all the gases generated by a burning coal spoil embankment has not been completed. However, it could be assumed that any other gas or a combination of several gases would have a detrimental effect on humans, animals, and plant life in the immediate area of the spoil pile. In the past it has been difficult to accurately evaluate the total environmental effect of such a fire over a period of time. This information may be available in populated areas within the next few years.

CHAPTER II

CHARACTERISTICS OF COAL SPOIL

2.1 Physical Properties of Coal Refuse

Refuse produced during the coal cleaning operation varies in content and size according to the particular location and separation processes used to clean the coal. A typical coal refuse product can vary in diameter from greater than four inches to less than one-quarter inch in coal cleaning processes. Most subsurface material in hot spots is generally between one-quarter inch to two inches.[3] Average refuse or chitter consists of coal, rock, carbonaceous shales and pyrite. In addition, most dumps have more combustible materials such as wood, greasy cloths, paper, ropes, rubber, and various plastic containers. Average refuse is estimated to contain less than 25 percent of combustible matter but poor separation techniques have left thousands of tons of coal on spoil piles. Table 6 shows a percentage range for typical chemical analysis of spoil piles.

Spoil in the Warrior coal basin varies with the location and with the geology of the rock surrounding the coal seams. Warrior basin coal is generally low in sulfur and iron. Refuse samples from the washer product vary from greater than five inches to minute particle size. However, haulage and transportation tend to break up the larger particles leaving the average rock in the spoil pile in less than a

TABLE 6

CHEMICAL ANALYSIS OF REFUSE SAMPLES

	Percentage Range for Several Samples %
Air-dried Basis	
Moisture	2.2 - 2.7
Ash	42.3 - 65.9
Volatile Matter	17.3 - 30.2
Fixed Carbon	14.6 - 24.8
Sulfur - Total	1.43 - 5.92
Pyrite	0.11 - 0.23
Sulfate	0.42 - 1.14
Organic (difference)	0.53 - 4.55
Fixed in Ash	0.0 - 0.2
Carbon Dioxide	0.03 - 0.13
Carbon (Uncorr. for CO_2)	22.0 - 40.4
Hydrogen	2.2 - 3.4
Nitrogen	0.5 - 1.6
Sulfur (organic)	0.5 - 4.6
Oxygen (difference)	6.7 - 7.3

(Flann and Lukaszewski 6)

three and one-half inch size. Shale is the most abundant rock that can be easily identified along with the small amounts of coal.

The physical properties of the coal and the surrounding conditions of the environment determine the tendency for natural oxidation and spontaneous combustion for a spoil embankment. The actual oxidation of coal involves several independent overlapping processes that are generally dependent on the pile itself. Initially, there is an absorption of moisture and oxygen, degradation by weathering, and an increase in heat whether it be externally or internally enhanced. Next, the products produced by weathering, carbon monoxide, sulfates, carbon dioxide, iron sulfides and sulfur, combined with this heat and other independent variables, create the conditions necessary for oxidization to occur. Once oxidation has started, a sufficient inflow of oxygen must be available for the process to continue.[6]

2.2 Combustion of Coal Refuse

Four factors which always determine the development and progression of fire in a coal embankment are

1) Composition of the refuse
2) Location of the embankment
3) Construction of the dump
4) Variations in the weather.

The reactivity of coal waste varies according to the location, source and composition. These factors should be evaluated to prevent a material known to oxidize rapidly as temperature increases from being mixed with other combustibles or any cellulosic materials of low ignition temperatures.

The proper disposal area would discourage solar radiation build-up, minimize air current exposure and avoid water courses. Any physical features which encourage the access of air flows and impede the loss of heat should be considered. Steep grading and poor consolidation tend to propagate a fire. The weather can play a major role in fire promotion, since the natural process of oxidation is accelerated by high ambient temperatures and solar radiation. Hot, dry weather encourages heat retention and leads to self-heating and ignition.

Spoil embankment fires are extremely difficult to extinguish. The fire spreads by the influx of new air at a rate directly proportional to that influx. The oxidation process is further encouraged by the upward movement of hot air and combustion gases, creating a draft which makes the fire self-sustaining. The combustion started at the flank is spread inward and downward through porous zones and is supplied with fresh air from channels in the burned zone. The fire is rapidly spread by any woods, grass or brush surrounding the refuse. In many cases an insufficient inflow of oxygen exists to propagate the fire. However, the combustion in the hot spot causes subsidence which creates cracks and fractures along the combustion zone and provides the additional ventilation ducts to propagate the fire.[6]

The pattern of burning was similar in all dumps investigated. Major combustion zones were generally on the western sides of the spoil banks, always peripheral and developed into combustion fronts advancing toward the center of the spoil embankment.

Many times a repetitive pattern of ignition develops, depending on wind direction and velocity. As more air enters the base, more spoil is oxidized and at a more rapid rate. The smoking at the edge indicates

the initial stages in the life of a fire, which propagates inward causing large cracks as the fire ages.

As the material is consumed, the burning section caves in and cuts the air ducts and smoking resumes. The material which caves in is reduced to ash and the next section is undermined. The entire process may be stimulated by local "red dog" poachers who remove the ash for various uses. The fire will continue to follow a favorable course until the center of the dump is reached. At that point the fire is generally out of control and will probably engulf the entire dump. Figure 1 shows the cross-section of a burning bank. The fire seat may be only a hot spot or it may be a hot front that extends as far as half-way around the the embankment. A full-scale investigation of the dump is needed to determine the total extent of the fire.

The several products of oxidation and combustion are both solid and gaseous. Weathered spoil is gray in color when dry but its appearance is altered when heated. As oxidation occurs the heat produced causes the movement of moisture, as illustrated by steam rising on cold mornings from a hot spot. Iron sulfates, sulfur and sulfuric acid are products of the sulfide elements in the oxidation process. The acid then reaches the alkaline minerals and dissolves them. The salt solutions are carried to the surface where they dry. These deposits of white and yellow flakes and deposits on the surface of a dump are indicative of internal heating. Generally, oxides of sulfur may be smelled around a burning dump. Coal tar is also a by-product of coal oxidation. The terminal residue is a red porous inert ash commonly called "red dog."

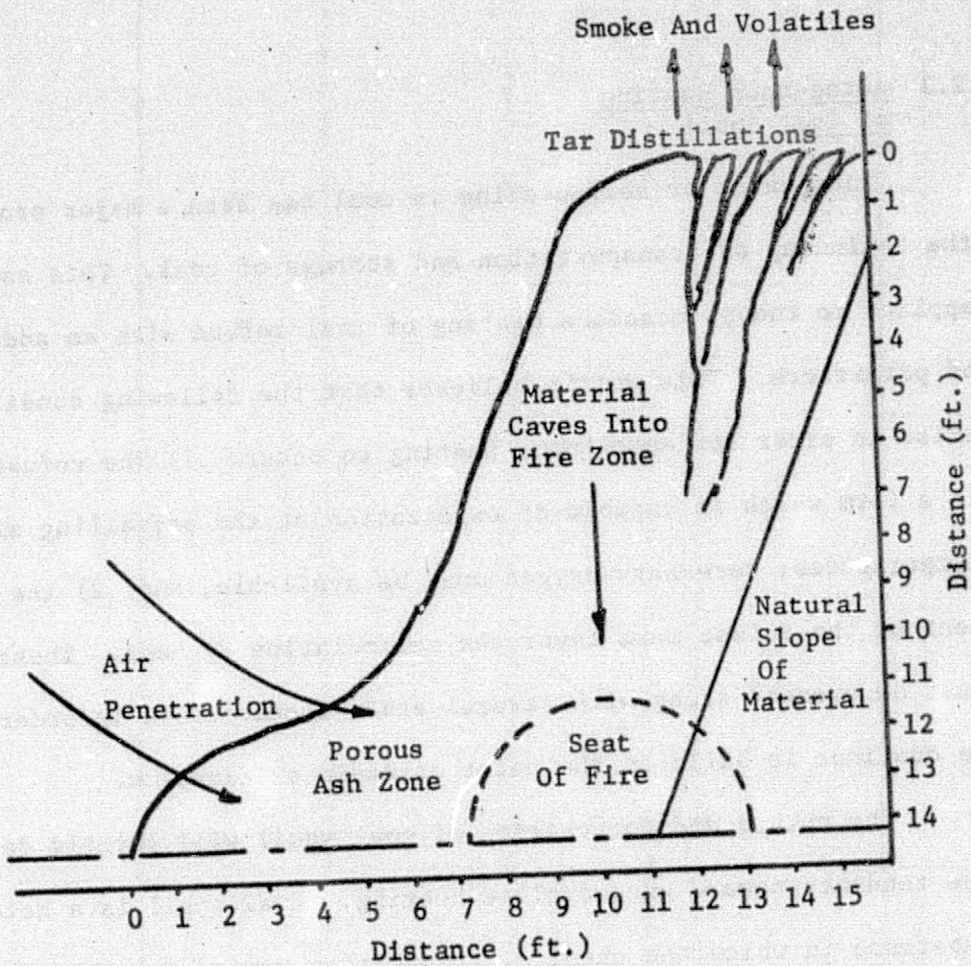

Figure 1. Cross Section of a Coal Spoil Fire (After Flann and Lukaszewski [6])

In addition to the solid constituents of a fire, various gases are produced in association with the oxidation and combustion processes. These include methane, sulfur dioxide, carbon monoxide and hydrogen sulfide.[6]

2.3 Autogenous Heating of Coal Spoil

Autogenous or self-heating in coal has been a major problem since the beginning of transportation and storage of coal. This same problem applies to the spontaneous heating of coal refuse with an added number of parameters. This writer believes that the following conditions must exist in order for autogenous heating to occur: 1) The refuse must be in a form which is capable of oxidization at the prevailing ambient temperatures; necessary oxygen must be available, and 2) the environment of the refuse must favor the accumulation of heat. These factors must be present along with several other accelerators in order for heat to continue to build to the point of rapid oxidization.

The nature and composition of coal spoil will largely determine the tendency toward uncontrolled heating. Coal spoil is a heterogenous substance in which the chemical composition varies greatly with geology, mining conditions, and separation techniques. In addition, it has been proven that the coal constituents vitrain and clarin are more susceptible to rapid oxidation than others. Mineral impurities such as sulfur and pyrite enter into the heating process along with high moisture content. The heat which is produced during the absorption of water, and liberated during weathering and slow oxidation is the initial heat production in the autogenous heating process. The area of surface of the refuse that is exposed to ambient temperatures, coupled with the

compaction and pressure, control the parameters of oxygen inflow and the dissipation of heat. This over-all concept has been diagrammed in Figure 2. There appears to be some critical temperature that is reached in each refuse pile before the oxidation becomes rapid enough to be termed a "fire." Depending upon the variables of the bank, at such a time when the autogenous heat reaches the critical point, the heat will increase at a rapid rate to become a fire or either the temperature will reach some maximum crossover above the critical temperature and only slow oxidation would occur within the refuse.[7] The following is an oversimplified explanation of the maximum crossover temperature:

$$MCT = \text{Function of}$$
$$(Cm + Oi + Hr + A + t)$$

where

MCT = maximum cross-over temperature

Oi = oxygen inflow

Hr = heat retention

A = accelerators

Cm = carbonaceous material

t = time.

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It is impossible to quantitatively evaluate each of these parameters but bank conditions can be simulated to approximate a "run-away" point or one where the change in temperature to the change in time becomes abnormally large for some range of temperatures above the maximum crossover temperature. This can be mathematically explained by

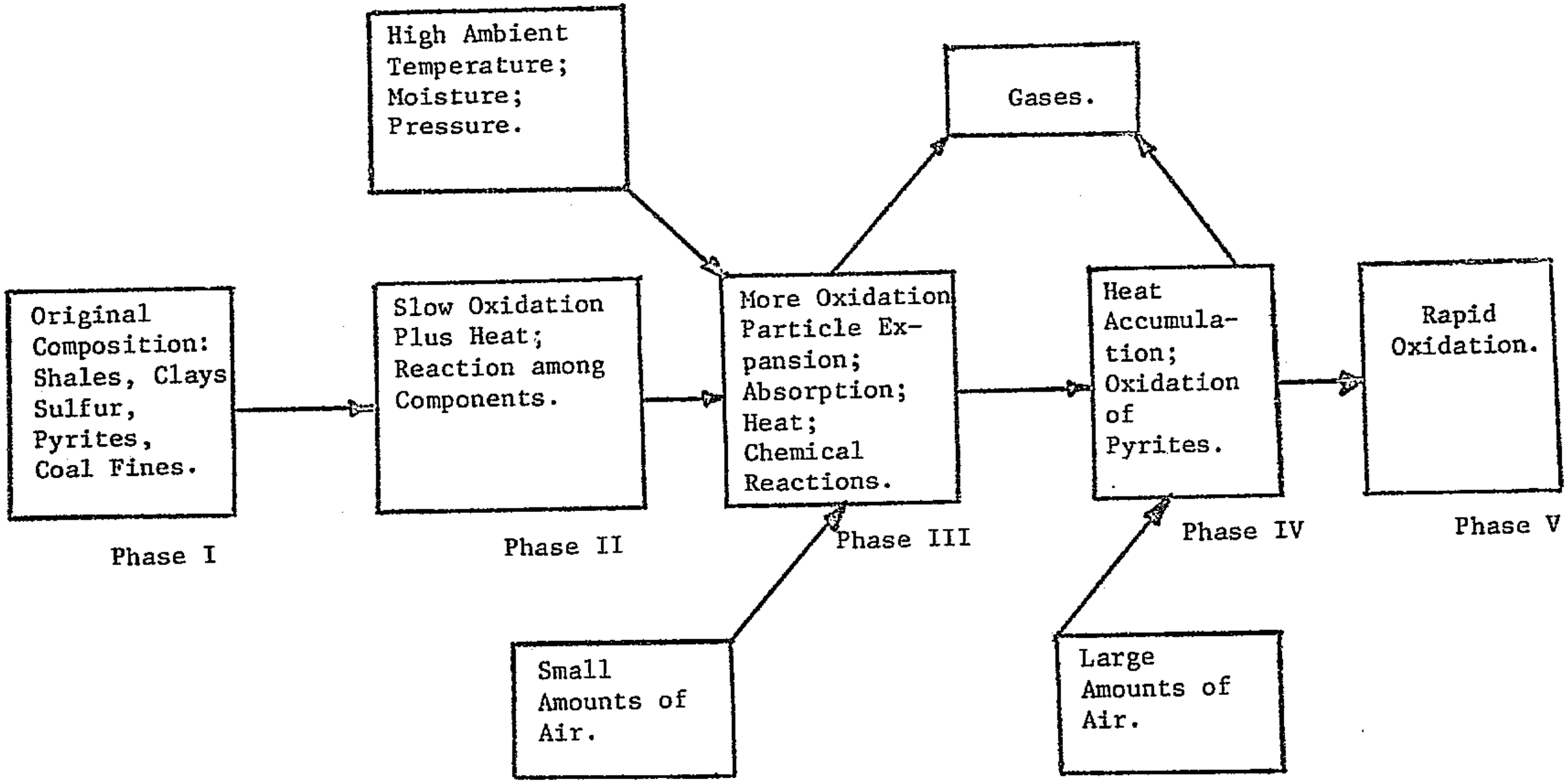

Figure 2. Concept of Autogenous Heating

$$\Delta\lambda >> \Delta\alpha \quad ,$$

where

$\Delta\lambda$ = temperature rise above MCT and

$\Delta\alpha$ = normal temperature rise.

This concept can be seen on Figure 3. The maximum temperature of combustion is determined by the Btu value and is never reached due to the limiting parameters and nature of the spoil. In this figure, refuse #1 would burn or rapidly oxidize and refuse #2 would not.

A series of experiments were conducted by Irons and Spicer[7] to establish maximum crossover temperatures and its relationship to air inflow which is expressed in Figure 4. The analysis for the refuse sample is as follows:

Run-away, ^{o}F	- 300
Ash %	- 57.3
Sulfur %	- 19.5
Btu/lb	- 5254
Volatile matter %	- 18.0
Bulk density lb/ft^3	- 70.4

Tests were conducted on 11 refuse piles in which the internal temperature, the Btu value, the ambient temperature, and the refuse size was recorded for correlation. The spoil piles were constructed in such a manner that they would be most susceptible to spontaneous combustion. The conclusions are listed below:

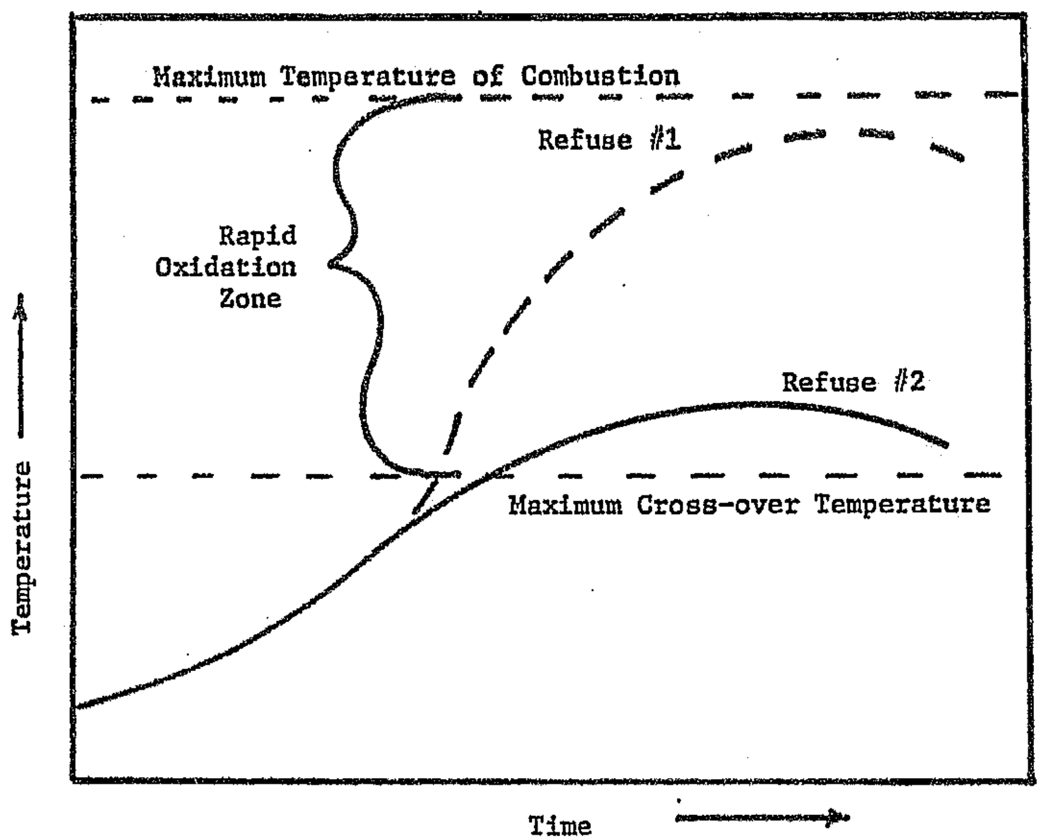

Figure 3. Maximum Cross-over Temperature
(After Irons and Spicer 7)

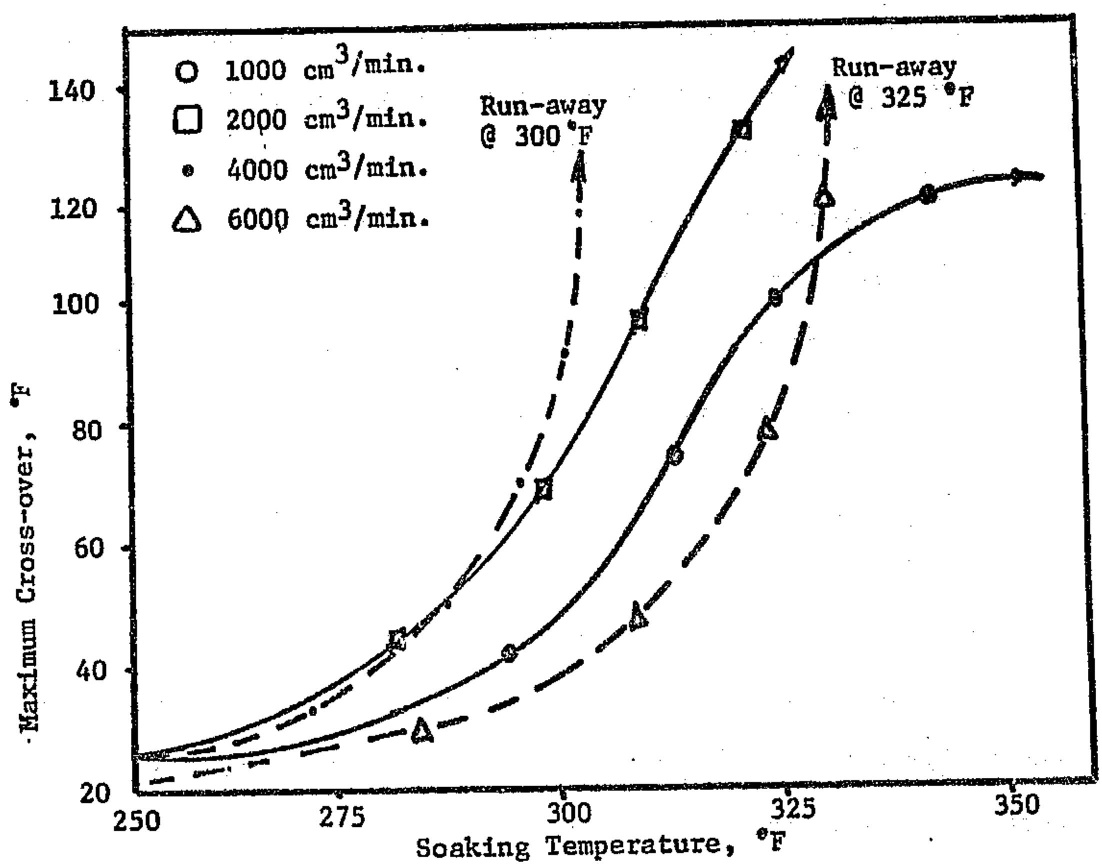

Figure 4. Effect of Airflow on Maximum Cross-over Temperature (After Irons and Spicer 7)

1) A run-away temperature can be established for a particular refuse if it has the proper spontaneous potential and oxygen inflow.

2) Run-away temperatures for bituminous refuse are lower than for anthracite refuse.

3) The ash content directly affects the maximum crossover.

4) Ignition occurs when the run-away temperature is exceeded.

5) The process of autogenous heating was indicated to be a particle surface oxidation phenomenon.

6) The investigation did not reveal the maximum carbon and sulfur contents that refuse could carry without being vulnerable to spontaneous combustion.[7]

2.4 Heat Transfer in Coal Spoil

In order to fully understand the phenomenon of coal spoil fires, the characteristics of heat transfer should be defined. Historically, engineers have believed that a spoil embankment could actually burn internally for several months before the effects could be seen on the surface. The purpose of this heat transfer analysis is to determine the time and rate of temperature conduction in coal spoil by construction of an approximate mathematical model. The model was then computerized with many parameters changed sequentially to present a range of data for solutions.

Several problems were encountered when applying the coal spoil to a mathematical model. First, the coal spoil is not homogenous in any dump, much less in several dumps. The density varies greatly according to shale content, mineral matter, and coarseness. The amount of moisture

is variable throughout the dump. The heat released per pound of spoil is variable throughout the spoil pile, consequently the specific heat and thermal diffusivity are variable.

The model used in this study employed a constant strength line heat source in an infinite solid.[8] The mathematical model used in this study was:

$$Y = \frac{Q}{RC}\left[\frac{(1)}{(4\pi at)}\right]^{3/2} e^{-(3r^2)/4at}$$

Where

Y = temperature change in ^oF

Q = heat released in Btu

R = density of material in lb/ft^3

C = specific heat in Btu/lb ^oF

a = thermal diffusivity in ft^2/hr

t = time in hours

r = radius in feet[7]

In the computerized mathematical model the following were assumed:

$R = 80\ lb/ft^3$

$C = 0.5$ Btu/lb ^oF

$a = 0.01\ ft^2/hr$

The heat build-up was investigated at a ten-foot radius assuming spherical heat release from the source. Values of t were varied from 200 to 8,000 hours and the heat source was varied from 5,000 to 2,000,000 Btu. The computer program using FORTRAN IV is given below.

```
PI = 3.1416
M = 4
N = 200
RHO = 80
CP = .5
ALPHA = 0.01
```

```
      X = 10
      DO  40  K=1, M
      READ (5,2) Q
2     FORMAT
      T = 100
      DO 10 J=1, N
      T = T+100
      A = 2.718** (-(3*X**2) / (4*ALPHA*T)
      B = (4*PI* ALPHA *T) ** (-3./2.)
      Y = Q*A*B / (RHO*CP)
      WRITE (6,30) Q,T,Y
30    FORMAT ('O',20X, F10.0, 10X, FI0.0, 10X, F20.10)
10    CONTINUE
40    CONTINUE
      STOP
      END
```

The results of the program are plotted on two-cycle semi log paper in Figure 5. It was observed that all of the curves became a maximum at approximately 7500 hours, which is nearly 10.5 months. However, different radii would yield different maximums at each Btu value. In Figure 6 the heat generated was plotted against the maximum temperature build-up to obtain the maximum temperature rise for different amounts of heat generated. Such a correlation would be useful in determining the heat generated for varying amounts of surface temperature build-up. As seen in this figure a temperature rise at the surface of 35^{o}F would be generated by 3.8 (10^{6}) Btu at a distance of 10 feet.

In summary a mathematical model can be designed to predict heat transfer in coal spoil embankments. However, the accuracy of such a model is dependent upon the homogeneity of the spoil and the accuracy of the values assumed for the various parameters. To accurately apply a mathematical model, the spoil embankment should be thoroughly sampled and a chemical analysis of each sample should be completed for accurate data assimilation in the formula.

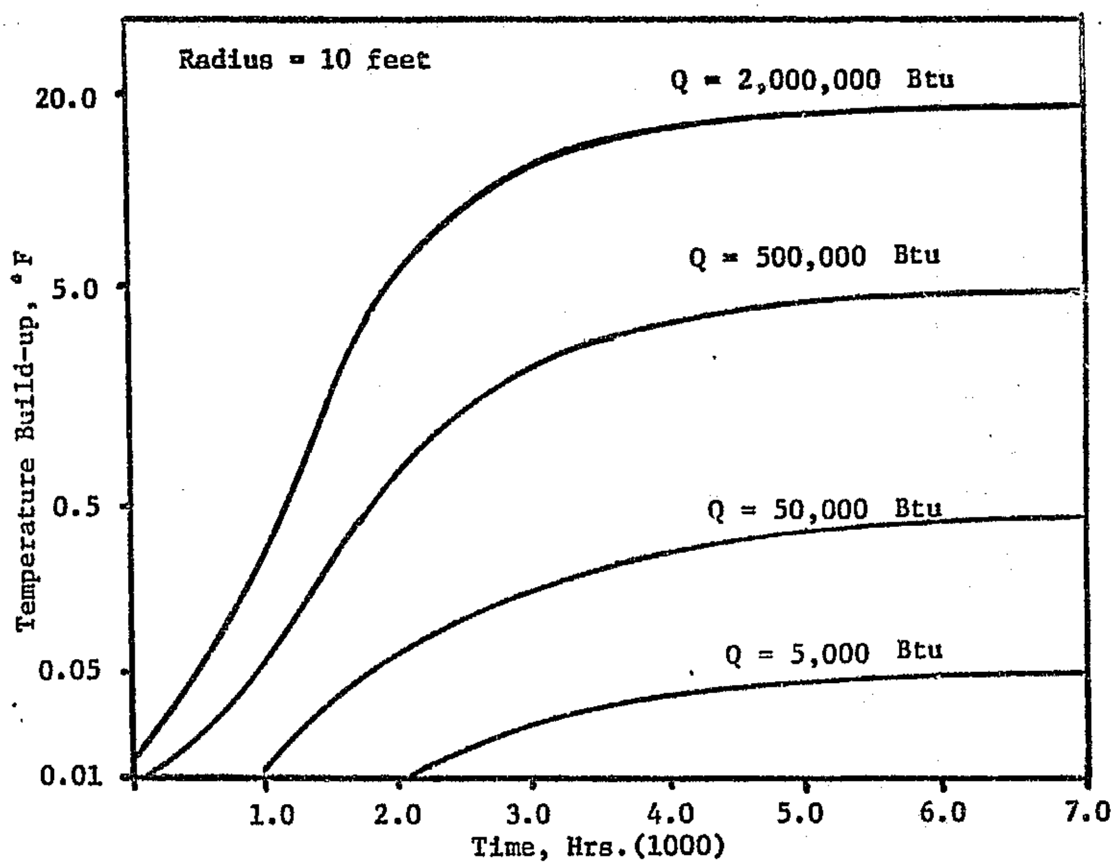

Figure 5. Temperature Build-up Vs. Time

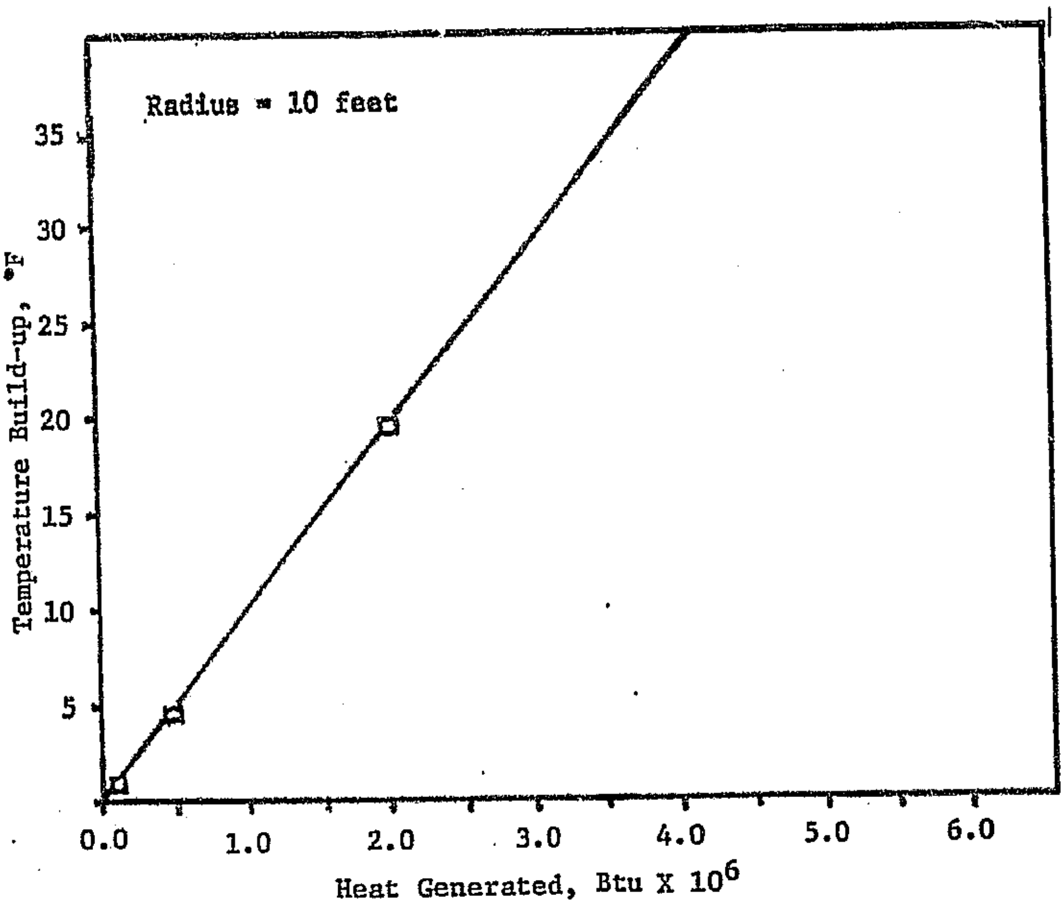

Figure 6. Maximum Surface Temperature Build-up

CHAPTER III

REMOTE SENSING

3.1 Electromagnetic Radiation

Remote sensing, one of the most popular mass data-gathering techniques, may fall into five broad categories according to sources of energy: sonic, electrical, nuclear, magnetic, and electromagnetic radiation. Seldom would all of these techniques be applied to one objective, but each contributes useful information and data for specialized cases. It is the objective of this study to focus upon applications of remotely-sensed data from electromagnetic radiation for the detection of fires in coal spoil embankments. Applications of the other techniques and sources of remote sensing will not be discussed in this text.

Electromagnetic radiation may be divided into many ranges, several of which are presented in this report. Radiation that can be photographed with a camera is called actinic radiation. However, actinic radiation comprises only a very small portion of the electromagnetic radiation spectrum.

A beam of white light can be dispersed by a crystal prism into a spectrum, which includes a band of color from violet through blue, blue-green, green yellow, orange, red and deep red. These colors are separated because they represent light of different wave lengths; these wave lengths become longer as the spectrum is traversed from blue to red. The range of wave lengths perceived in the visible spectrum

varies from 400 nm at the blue end to 700 nm at the red end. A nm (nanometer) is defined to be one millionth of a millimeter. Figure 7 shows the spectrum and the system used in this report in the various wave lengths.[9]

In addition to the light which is visible, there also exists invisible electromagnetic radiation similar to the visible radiation called light. This invisible radiation is present at both ends of the visible spectrum. Short wave length radiation, called ultra violet radiation exists beyond the violet radiation. It is invisible, but has a strong action on photographic materials, making it highly actinic. At the other end of the visible spectrum, the infrared (beyond the red) region exists.

As the infrared region extends far beyond the end of the visible region, the wave length increases, creating heat waves and finally merging into radar and radio waves. Even though the infrared region is extensive, only the region near visible-red is actinic. The longest wave length of radiation recorded by photography is about 1350 nm, but usually infrared photography is in the 700 nm to 900 nm range. Beyond this range, storage and use of specialized film would be impractical because of the amount of heat radiated. Even body temperature is enough to fog film. For some applications now served by thermal recording, such specialized film would have to be stored at the low temperature of liquid nitrogen.[9]

Infrared radiation can be separated into four broad ranges of increasingly longer wave lengths:

1) The actinic range, which comprises the near-red part of the radiation produced by incandescent objects such as the sun and electric

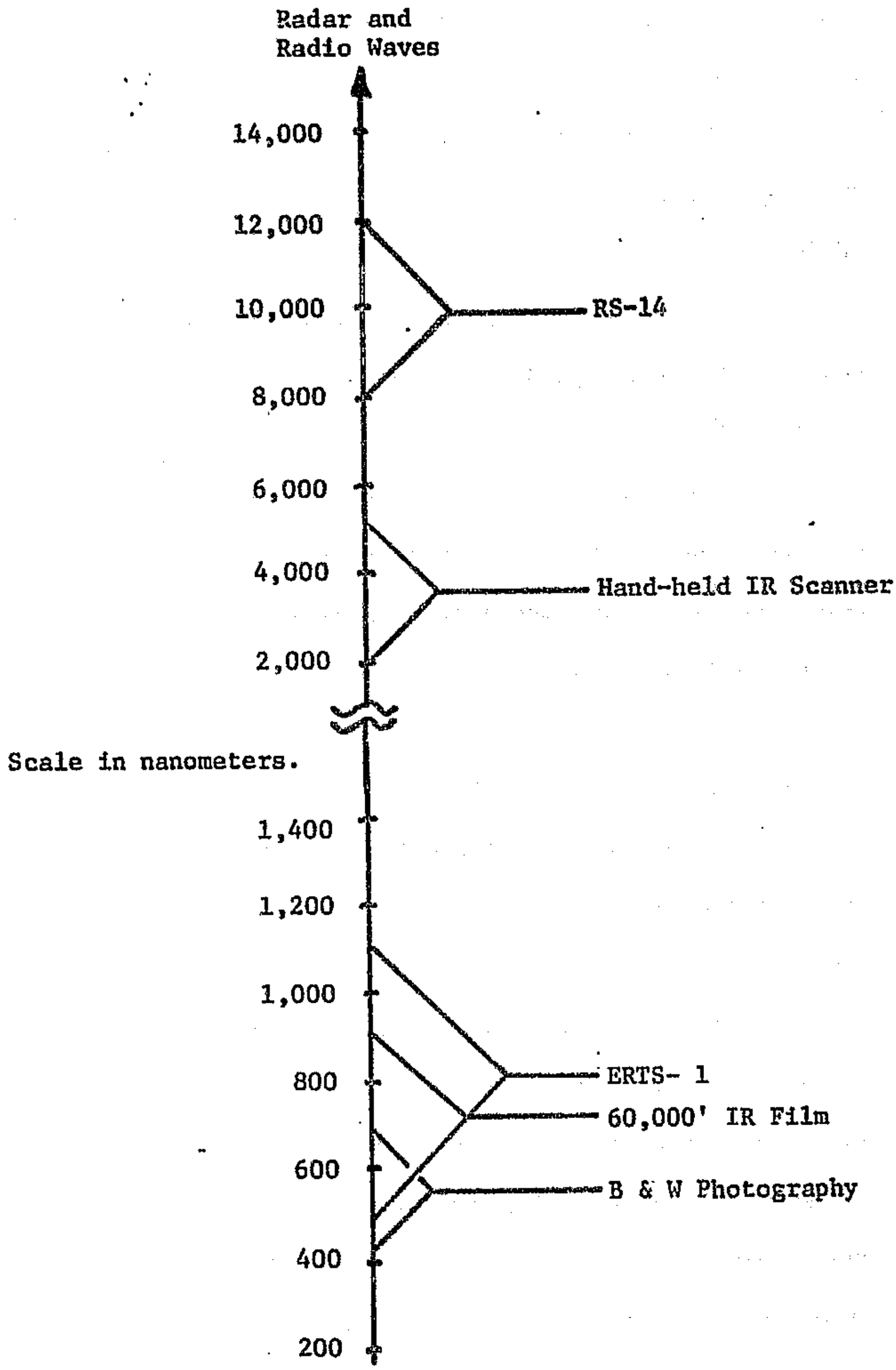

Figure 7. The Electromagnetic Spectrum

lights. This radiation can be reflected or emitted by objects that are not hot themselves.

2) The hot-object range which comes from nonincandescent objects such as hotirons or electrical components, having temperatures around 400°C.

3) The calorific range of radiation, produced by objects with temperatures around boiling water and steam pipes, having temperatures around 200°C.

4) The warm range of radiation produced by human body temperature and ground heat. Radiation in the warm range is from 8,000 to 14,000 nm.[9] The hot spots in coal spoil embankments will overlap ranges three and four.

3.2 ERTS-I Photography (Visible and Near Infrared Actinic)

The ERTS-I module is a sun-synchronous satellite with essentially two function systems: a Multispectral Scanner Subsystem (MSS) and a Return Beam Vidicon (RBV) camera. In addition, the satellite has a Data Collection System (DCS) to gather water quality information supplied by Data Collection Platforms (DCP's) located in strategic water locations. Figure 8 is an illustration of the ERTS-I satellite. Due to technical difficulties the RBV system has been inoperative since the launch of the satellite. However, the two remaining systems continue to function properly. Only the data from the MSS subsystem was used in this study.

The first and primary sensor functioning on ERTS-I is the MSS system and is composed of a scanning device and an oscillating mirror to continually scan the earth's surface. (The schematic of the MSS

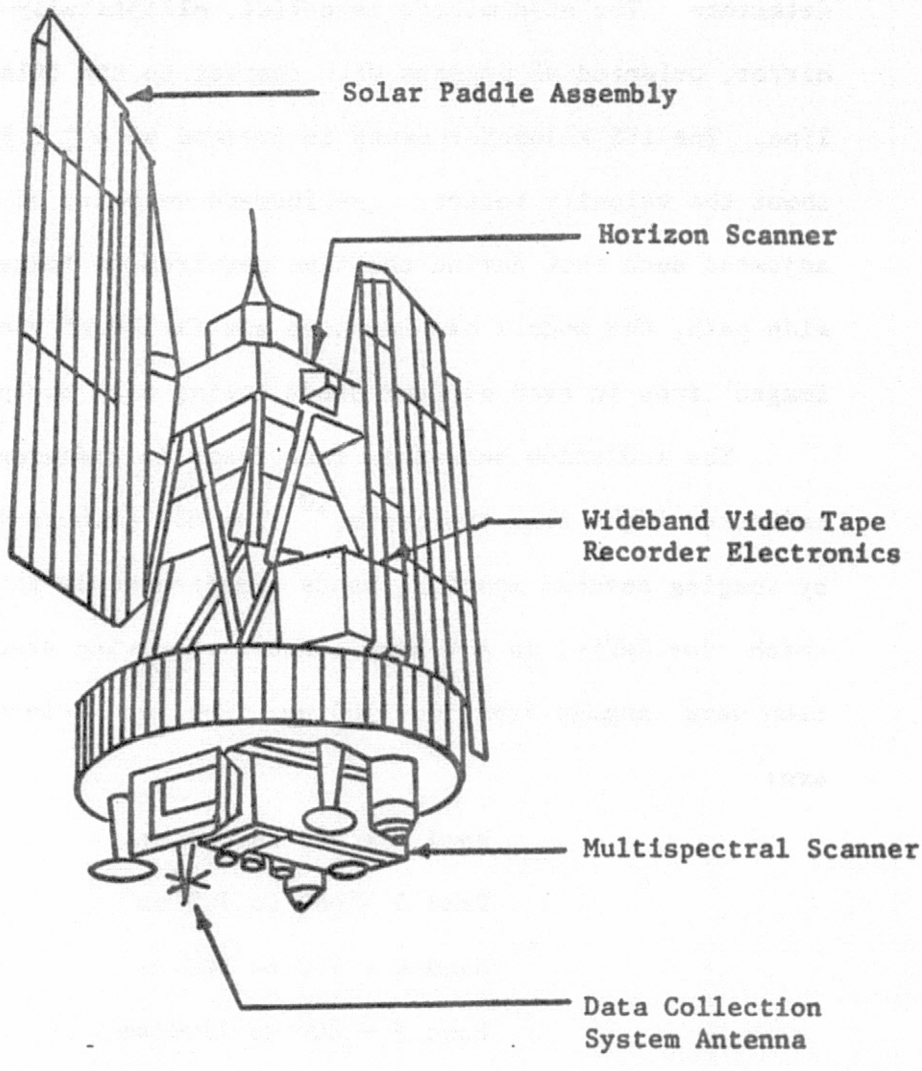

Figure 8. The ERTS-I Satellite
(After Data Users Handbook 10)

is shown in Figure 9.) The subject system is composed of a scan mirror, a set of concave reflecting mirrors, and a convex mirror to concentrate the ground reflected light onto the fiber bundle which activates the detectors. The scan mirror is a flat, elliptically-shaped 9 x 13 inch mirror, oriented 45 degrees with respect to the telescope axis and nadir line. The 185 kilometer sweep is created by a ± 2.9 degrees rotation about the velocity vector. The forward velocity of the satellite is adjusted such that during the time required to image the 185-kilometer-wide path, the module has advanced six fields of view creating six imaged lines in each of four bands during each sweep.

The radiation sensed in each frame is different amounts of reflected light from the earth.[10] The MSS gathers data on the earth by imaging several spectral bands simultaneously through the same system which for ERTS-I is a 4-band scanner receiving electromagnetic radiation wave lengths from 500-1100 nm. The four selected spectral bands are:

Band 4 - 500 to 600 nm

Band 5 - 600 to 700 nm

Band 6 - 700 to 800 nm

Band 7 - 800 to 1100 nm

On board the module the light recordings are transformed into electrical energy, digitized, and sent to gathering stations on the surface.

Table 7 is a listing of all the products available for users of ERTS-I imagery. System Corrected Images are images that contain the radiometric and initial spatial corrections introduced during the process of video tape to film conversion but not corrections provided by the scene correcting system. Scene corrected imagery refers to the

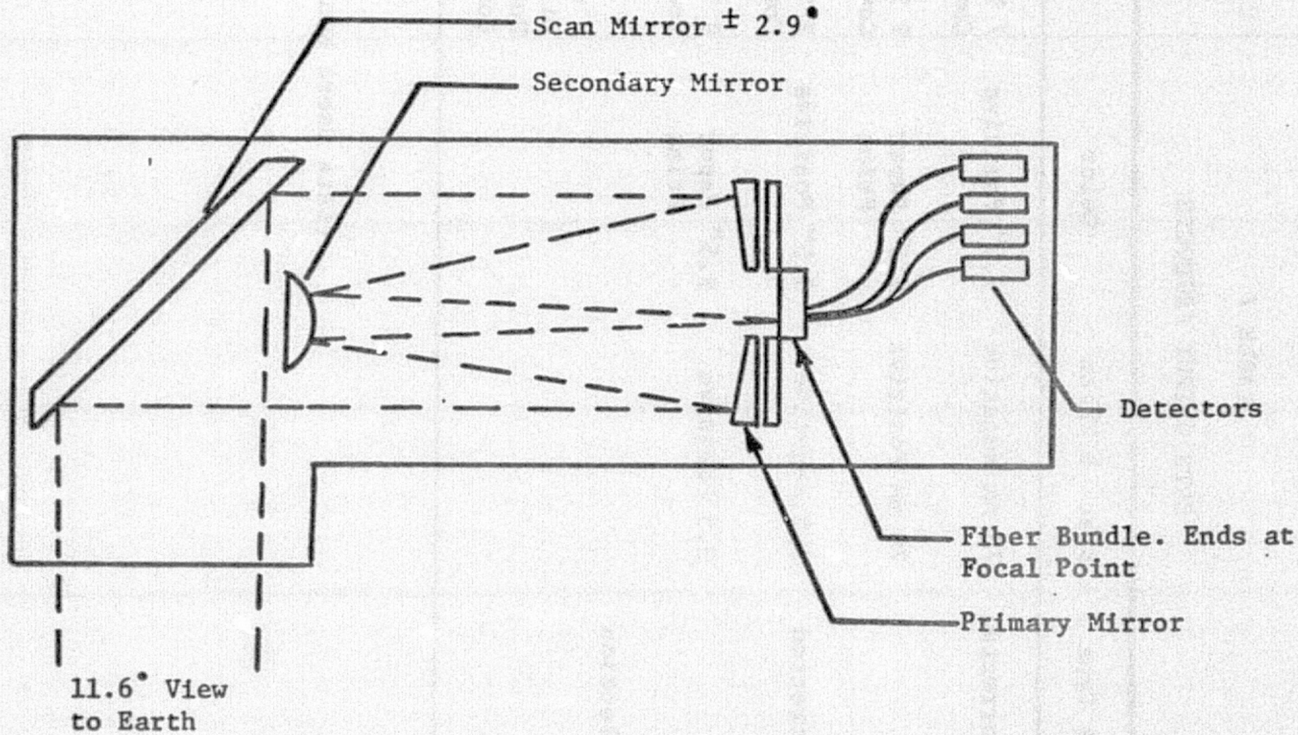

Figure 9. Schematic of Multispectral Scanner
(After Data Users Handbook 10)

TABLE 7

ERTS OUTPUT PRODUCTS

Product Type	Black & White	Color	Digital
System Corrected	70 mm Negative	9.5" Positive	7 Track Computer Tape
MSS	70 mm Positive	9.5" Paper Print	9 Track Computer Tape
Scene Corrected	9.5 Negative	9.5" Positive	7 Track Computer Tape
MSS	9.5 Positive	9.5" Paper Print	9 Track Computer Tape
Data Collection System			7 or 9 Track Digital Tape Punch Cards Computer Listing

(Data Users Handbook 10)

imagery that has received radiometric and spatial corrections provided by the scene-corrected imagery system including transformation into the Universal Transverse Mercator or Polar Stereographic coordinates. The most used and generally only available products are the 70 mm positives, which are scaled 1:3,369,000, the 9.5 inch positives, which are scaled 1:1,000,000, and the 9.5 inch paper prints. From the 70 mm positive transparencies, the writer uses ordinary development and enlargement techniques to produce a "posoprint." These posoprints have been especially useful in the location and identification of stripmines and spoil embankment dumps. The development technique will be discussed in Chapter IV.

Figure 10 is an example of a 9.5 inch print. Note the longitude-latitude tick marks along the sides of the image. An explanation of the alphanumeric annotation at the bottom of the image is as follows:

1) Character positions 01-08. 15APR73: Day, month and year of image.

2) Character positions 09-25. CN33-A/W087N: The longitude and latitude at the center of the image, indicated in degrees and minutes.

3) Character positions 26-42. N33-16/WO 87-22: The latitude and longitude of the nadir indicated in degrees and minutes.

4) Character positions 42-54. MSS 7: MSS indicates the system and the 7 indicates the band number.

5) Character positions 55-68. SUN EL55 AZ125: Sun angles - the sun elevation and azimuth as measured clockwise from true north.

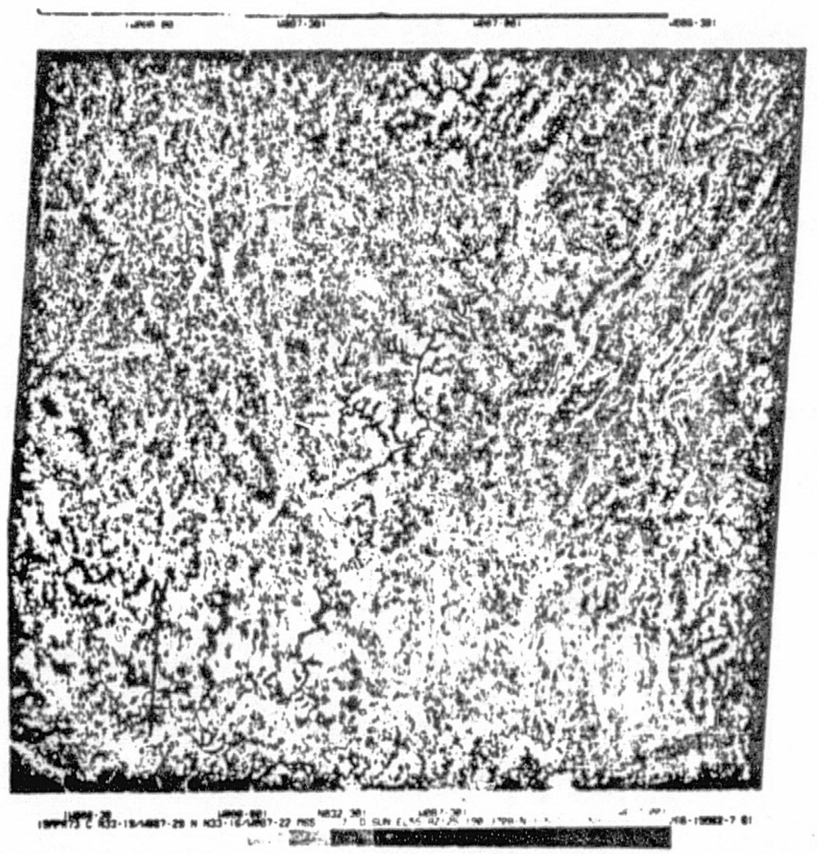

Figure 10. Reduced 9.5 Inch ERTS-I Print of the Warrior Coal Basin

6) Character positions 69-79. 190-3708-N: These indicate the spacecraft heading orbit revolution, and ground recording station.

7) Character positions 80-89. I-N-D-L: "I" indicates a full image, "N" indicates normal processing, "D" refers to definitive orbit and "L" refers to a "low gain" for a compressed mode of a MSS signal.

8) Character positions 90-98. NASA ERTS: Identifies the Agency and Project.

9) Character positions 99-114. E-1050-15551-5 01: Identifies project identifier, days after launch time of observation and regeneration number.[10]

3.3 Infrared Color Photography (Near Infrared Actinic)

Infrared color photography is a relatively new procedure which utilizes a color film sensitized to infrared. This film is commercially available from several sources. This type of film was originally produced for camouflage detection by aerial photography. However, it is now available in 35 mm magazines for numerous ground and laboratory uses. Unlike the usual color film, it has three image layers sensitized to green, red and infrared instead of blue, green and red. A yellow filter is used on the camera to withhold blue to which these are also sensitive. When processed, a yellow positive image records in the green-sensitive layer and positive images of magenta and cyan appear in the red, and infrared-sensitive layers (see Figure 11).

Even though blue has been excluded from the image by the yellow filter, blue can be formed in the transparency. Magenta and cyan will

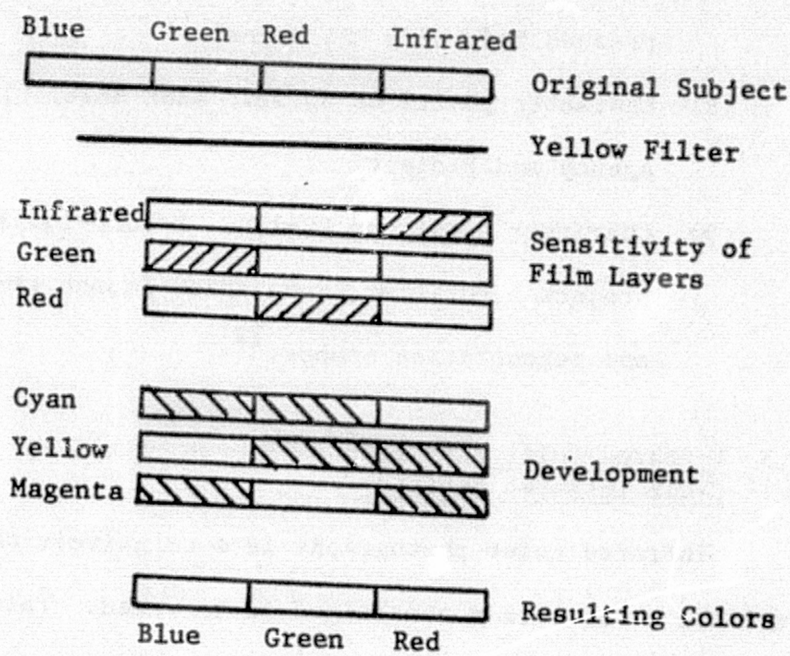

Figure 11. Color Formation With Infrared Color Film
(After Applied Infrared Photography 9)

predominate and will combine to form blue when the yellow image in the green sensitized layer is bright. Many other colors can be produced, depending on the proportions of green, red, and infrared reflected or transmitted by the subject. Leaves record red because they are "bright" in the infrared range; this produces a light-toned cyan image which allows red from the other layers to predominate.[9]

In addition, a visible-light component is integrated into the infrared record. The result is a "false-color" image of the subject. The film produces many characteristic colors in photographs of many physiological and botanical substances. Because the color infrared photography is relatively new, the infrared-reflection characteristics of substances have not been appreciated. The actinic infrared band is fully as wide as that from green to red, so several infrared "colors" could exist. It is only when the infrared radiations are translated by detailed photographic procedures into visible color differences that distinctions can be observed in a color photograph.[9] The infrared photographs in this report cover the spectral band range from 510 - 900 nm.

3.4 Hand-held Thermal Scanning (Medium Far-Infrared)

A thermal hand-held infrared scanner has been used successfully to detect temperature differences on direct-line-of-sight objects. The infrared (IR) scanner used to survey the coal spoil embankments in this report was one originally developed for military use as a device for night vision. The instrument used by the writer was furnished by the U. S. Bureau of Mines, Denver, Colorado. The device is shown in Figures 12 and 13. The IR scanner is powered by a 6-volt,

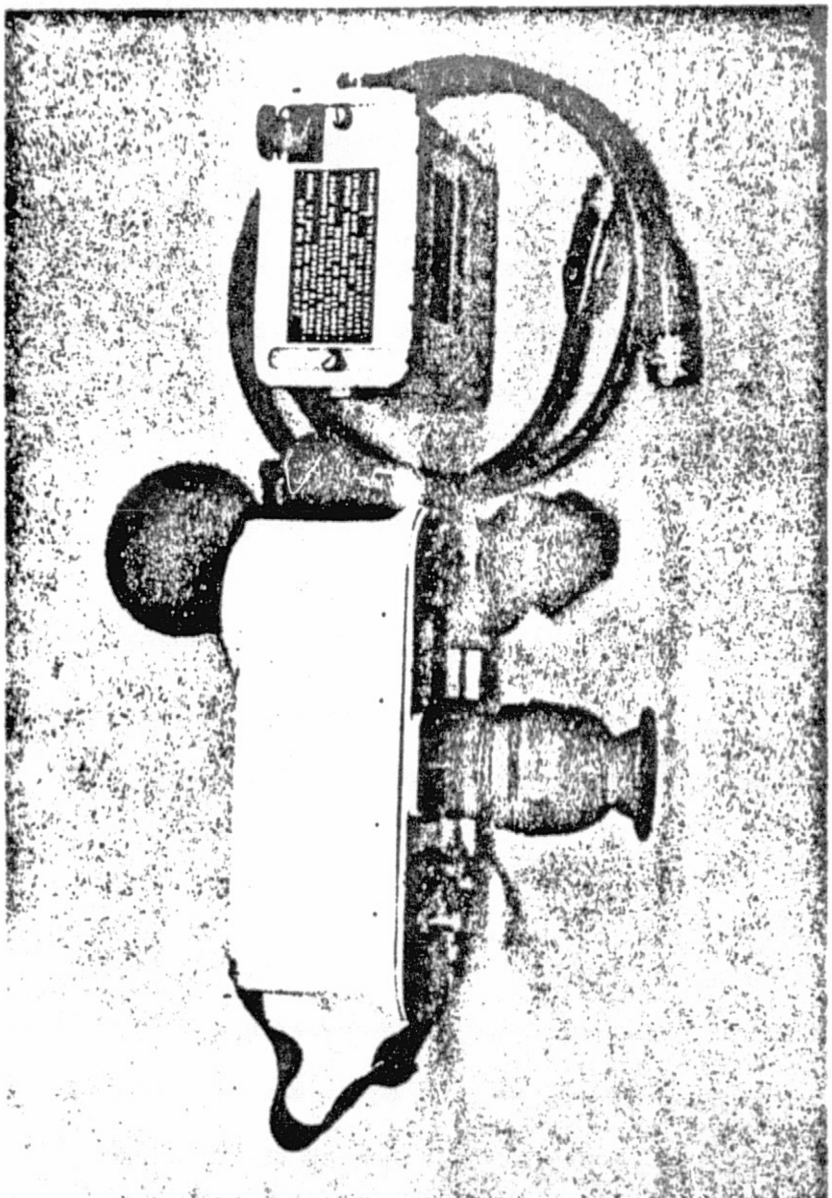

Figure 12. Top View, Hand-held Infrared Scanner

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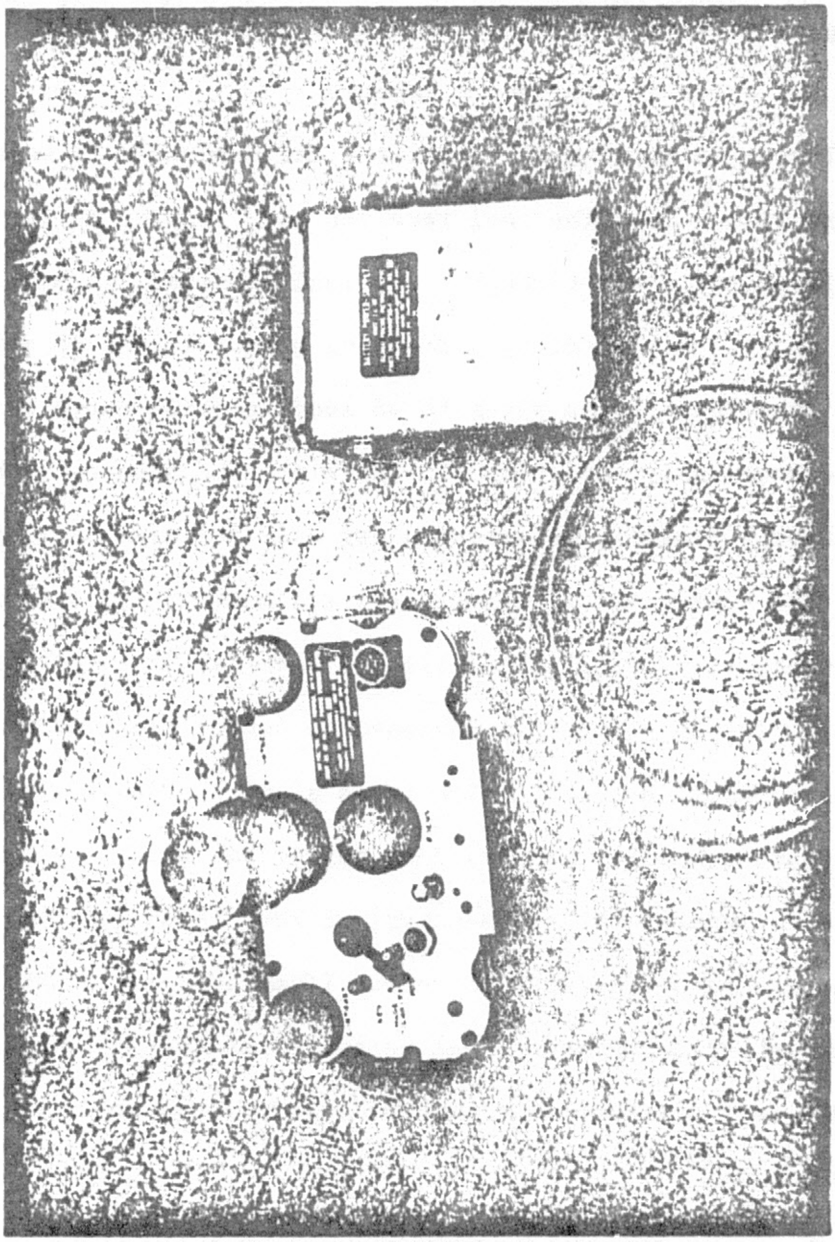

Figure 13. Back View, Hand-held Infrared Scanner

silver-zinc battery that is normally worn on a belt. The scanner itself is ten inches wide, 5.5 inches high, 3.5 inches deep and weighs six pounds. It is completely portable and is an ideal instrument for use in and around mining operations, for the detection of loose roof rock, geological anomalies, hot rollers in conveyor belts, and to detect hot spots in coal spoil embankments.

The major components of the thermal hand-held IR scanner are shown in Figure 14. The tool receives wave lengths in the three to five micrometer range through a 2.5 inch diameter, germanium silicone window that is reflected by a scanning mirror to the object lens. The object lens focuses the waves to 48 lead selenide detectors that are thermoelectrically cooled to 193° Kelvin. The signal is then amplified through a real-time synchronizer and displayed on a cathode ray tube. The instrument in effect is a radiometer with a thermopile and electronics to present a real-time, direct temperature reading on the display. The IR scanner is designed to detect temperature differentials as small as 0.2°C which is an adequate sensitivity for large temperature anomalies such as coal refuse hot spots. The maximum efficient range of the scanner has not been fully defined; however, it has been successfully used to detect fires at least 6,000 feet away. The coal spoil embankment fires were all identified from 2,000 feet to 3,000 feet altitude in a light aircraft in addition to ground observations.[12]

3.5 RS-14 Scanning (Far Infrared)

The RS-14 scanning system is a refined and sophisticated version of a basic hand-held scanner. The RS-14 receives electromagnetic

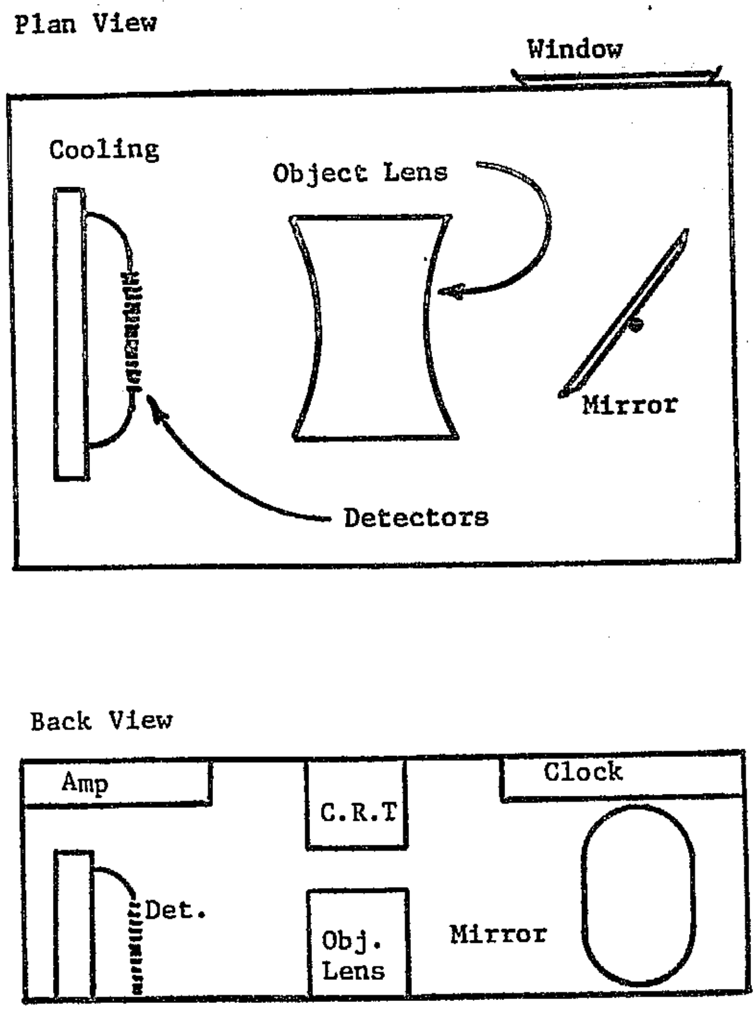

Figure 14. Components of the IR Scanner
(After Stateham 11)

radiation in the 8,000-12,000 nm wave length range. This radiation falls in the warm range; and due to the limits of the system, the RS-14 scanner is not capable of accurately recording temperatures greater than approximately 150°F.

The aerial RS-14 scanner receives radiation through an infrared-transmitting lens to a phosphorescent layer which is scanned with a heat sensor. The heat sensor impulses are amplified to a real-time synchronizer and displayed on a cathode ray tube. A camera, continuous film tape, or magnetic computer tape is focused on the display of the cathode ray tube where the image is recorded. Generally, the image is continuously reproduced on a positive transparency which is generally the same type of film used for Ektachrome transparencies. From this positive transparency, a negative transparency can be made for permanent paper reproduction.

CHAPTER IV

ELECTROMAGNETIC RADIATION ANALYSIS OF A COAL SPOIL PILE

4.1 Field Data

In order to fully and accurately evaluate the several remote sensing systems used in this study, it was essential to establish the existing embankment conditions as ground truth. These conditions may determine the usefulness of the different sensing systems that will be discussed in the summarization and recommendations. During this study thirteen coal spoil embankments were surveyed for effects of fires. The embankment selected, was the Parrish dump because it had visible effects of severe hot spots, it was conveniently located for observation, and the owners gave permission to study and report on the fires present.

The Parrish coal spoil embankment is located approximately three miles south of Parrish, Alabama. The spoil pile was begun in 1959. The refuse is primarily shales and jig-rejected coal having a combined heating value of 4,000 to 5,000 Btu per pound. The volume of refuse has typically ranged around 30 percent of the extracted tonnage. The Mary Lee coal, being mined at this location, has a shale layer separating two coal benches with two feet to six feet of coal being mined. Physical data for the dump are listed on Table 8.

TABLE 8

PHYSICAL DATA FOR PARRISH DUMP

Height: 70-90 feet

Acres: 12-15 acres

Age: 15 years

Approximate Tonnage: 5-6 million S. Tons

Heating Value of Spoil: 4000-5000 Btu/lb.

Geographical Coordinates: Lat. 33°42'10"
Long. 87°16'55"

Nearest Town: Parrish, Alabama

Population: 500

Distance to Nearest Town: 3 miles

The topography of the general area is a sequence of hills and valleys with the local relief being as much as 500 feet (Figure 15). A small stream flows on the western side of the dump. The spoil pile is the highest on the stream side, where the deepest part of the valley exists, and extends to the east and north as seen on an aerial photograph (Figure 16). The pile currently has four benches at its highest point and only one bench on the extreme northeastern flank.

The composition and texture of the spoil is variable thoughout the embankment. The older refuse appeared to be more fractured and weathered than the new refuse. About 80 percent of the old refuse was observed to be in irregular shapes from five cubic inches to ten cubic inches in volume. Ten percent of the old refuse was in pieces less than five cubic inches and greater than one cubic inch. The final 10 percent was less than one cubic inch in diameter. The new spoil appeared much larger than the old. Approximately 70 percent of the new spoil was composed of pieces greater than ten cubic inches and 25 percent appeared to consist of fragments between one cubic inch and ten cubic inches. The last five percent was less than one cubic inch in volume. It was evident that the spoil degenerated and weathered readily with time.

A fire was observed on the west side of the dump extending to the south side along the base of the dump. Smoke could be seen rising over the burning area (Figure 17), part of which has been covered with six to twelve inches of clay to cover the fire (Figure 18). This clay cover has been rendered ineffective due to natural erosion and compaction. Furthermore, the surface has subsided where the fire continued to burn allowing fresh air to rekindle the fires (Figure 19).

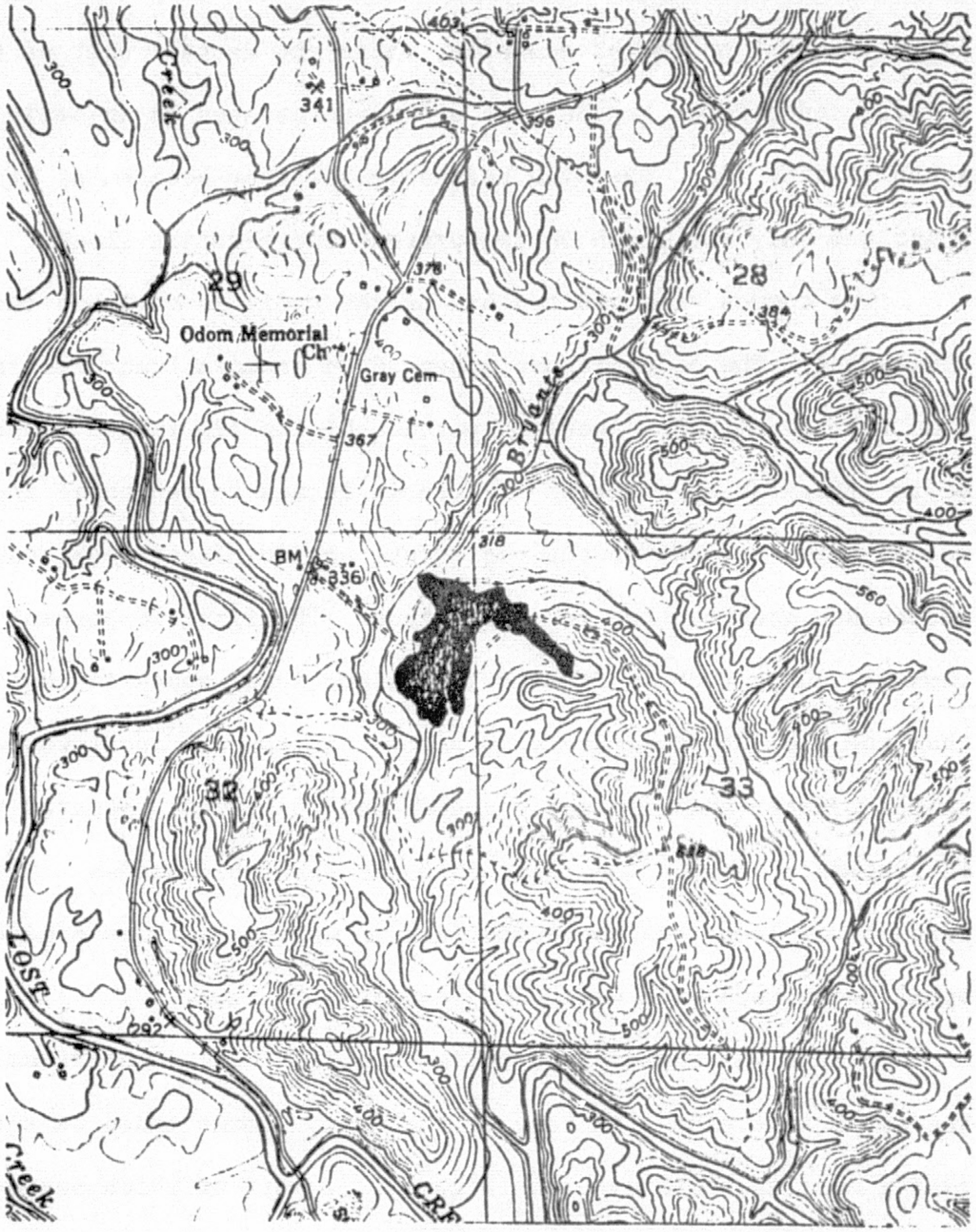

Figure 15. Topographic Map of Parrish Dump

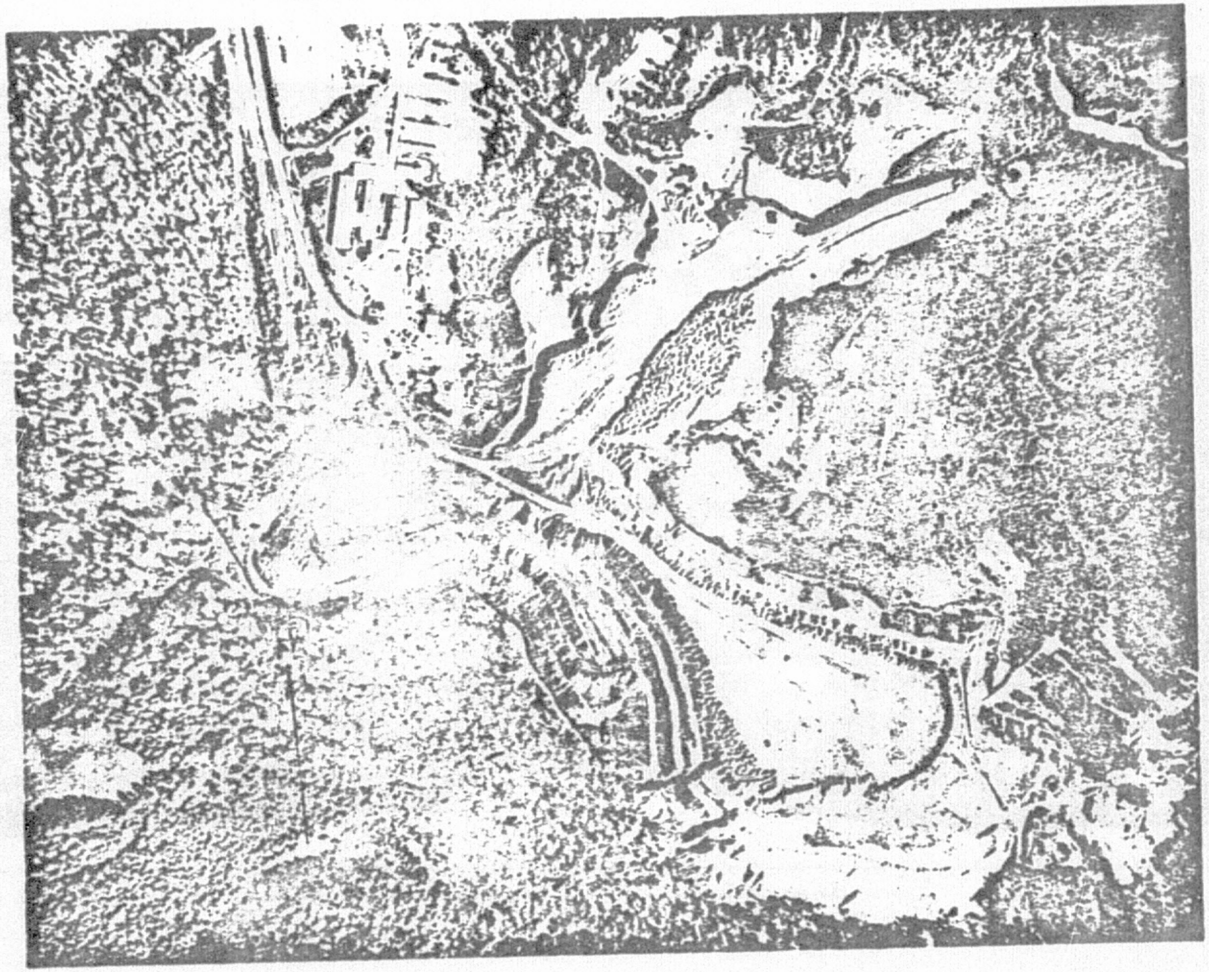

Figure 16. Aerial Photograph of Parrish Dump

Figure 17. Smoke on Parrish Spoil Pile

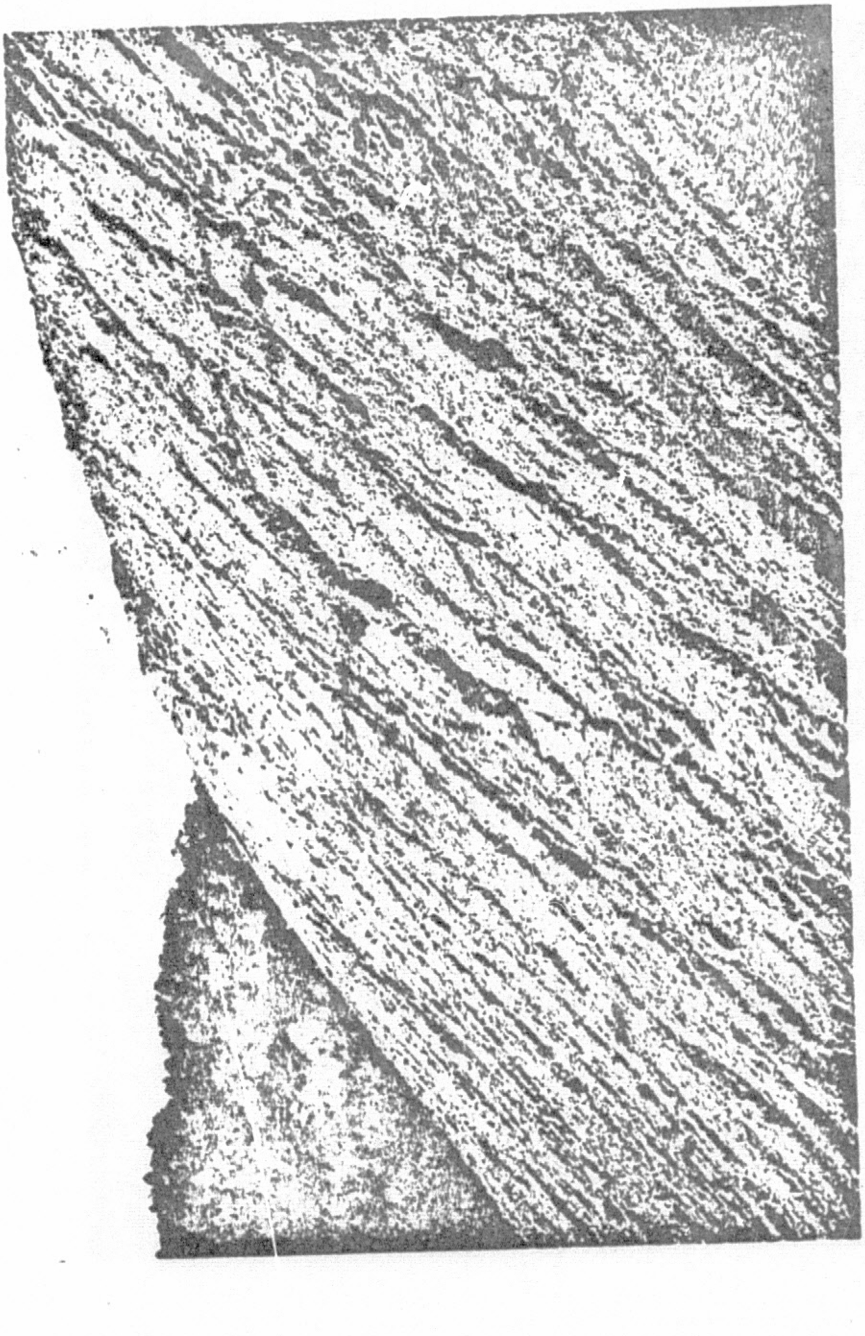

Figure 18. Clay Cover on Spoil

Figure 19. Slump in Clay and Surface

Temperature measurements were made on the areas where the hot spots and fires occurred. Normal surface temperatures measured with a hand radiometer were 84°F on sun-heated surfaces and approximately 140°F on the heated surfaces. These temperatures were confirmed with a thermocouple (Figure 20). The temperature ten inches under the surface ranged from 180-200°F, as measured with the thermocouple.

4.2 Low Altitude Black and White Photography

Low altitude (2,000-3,000 feet) black and white photography is an excellent visual tool to survey coal spoil embankments for external signs of fires and hot spots (Figure 16). Upon close examination of Figure 16, one can determine the distinct boundaries of the embankment, which is bordered on the west by the small stream and by the coal settling pond in the eastern cove.

When surveying the photographs for signs of fires or hot spots, discolored material is detectable on the south side of the dump, which is clay spread over a fire or hot spot to either impede the oxygen airflow or to cover the environmental effects of the fire. If the photography is made with sophisticated camera equipment and film, then the external effects of the fire may appear on the image. Upon close examination of the subject figure, small wisps of smoke can be seen rising over the west side of the embankment, indicating that a fire exists. However, simple hot spots or less severe fires probably would not be discernible from such an image. In addition, color photographs may be enlarged and enhanced to identify more facts which are not detectable on the black and white photographs.

Figure 20. Thermocouple in Spoil

Black and white photography is a useful imaging system to detect abnormal surface discolorations on a coal spoil pile. However, additional data are needed to identify warm and hot spots that have not been covered with clay or other inert material.

4.3 ERTS-I Imagery

Satellite imagery is a sophisticated system for repetitive coverage of the earth's surface. The full potential of this technique has not been realized, but investigations are continuing to exploit its uses. Each of the four bands of electromagnetic radiation wave lengths have different characteristics, and each is suited for optimum use in particular situations.

Bands four and five sense radiation wave lengths in the 500-600 nm and the 600-700 nm ranges, respectively. This visible actinic radiation may be photographed by ordinary means. These images are particularly useful in color changes in fields, tree vegetation, and urban areas. Even though most ERTS products are not in color, most practitioners feel that color enhancement is a needed dimension for the ERTS data user.

The most useful technique of enhancement the writer was able to use was the reversed image, which was named a "posoprint" for use in this study. The posoprint is made from a positive instead of a negative, which results in an image with reversed colors. These posoprints, along with the normal images in bands four and five were surveyed for the coal spoil embankments under study with mostly negative results. The reflected actinic light integrated with the reflected light of the surroundings to yield mostly indecipherable

boundaries. This problem was enhanced by the fact that the sensing mechanism was many miles away (the scale on a 9.5 inch print is 1:1,000,000). The image displayed no signs of the fires or the clay cover.

Bands six and seven, which receive radiation wave lengths from 700-800 nm and 800-1100 nm, respectively, were useful in the detection of the coal spoil embankments. Several of the spoil piles under study are circled on Figure 21, which is an enlarged posoprint of band six on April 15, 1973. On normal imagery these embankments would appear dark in relation to their surroundings but due to gray scale effects the contrast is better on the reversed image. These embankments appear to be indistinguishable from other like spots on the image to the unskilled ERTS user. The unskilled user must know what he seeks and its approximate location. Otherwise the image may be meaningless. The printed images did not show any distinguishable characteristics to indicate the presence of fires or hot spots on any of the spoil embankments. However, computer analysis of such data may indicate much more than the eye can detect. Practical application of the computer for this use is still in the future.

Data quality is variable due to problems in transfer and mechanics. The frequency of data is an advantage if no clouds cover the target areas. The writer found cloud cover to be a major problem in the repetitive data gathering process. The

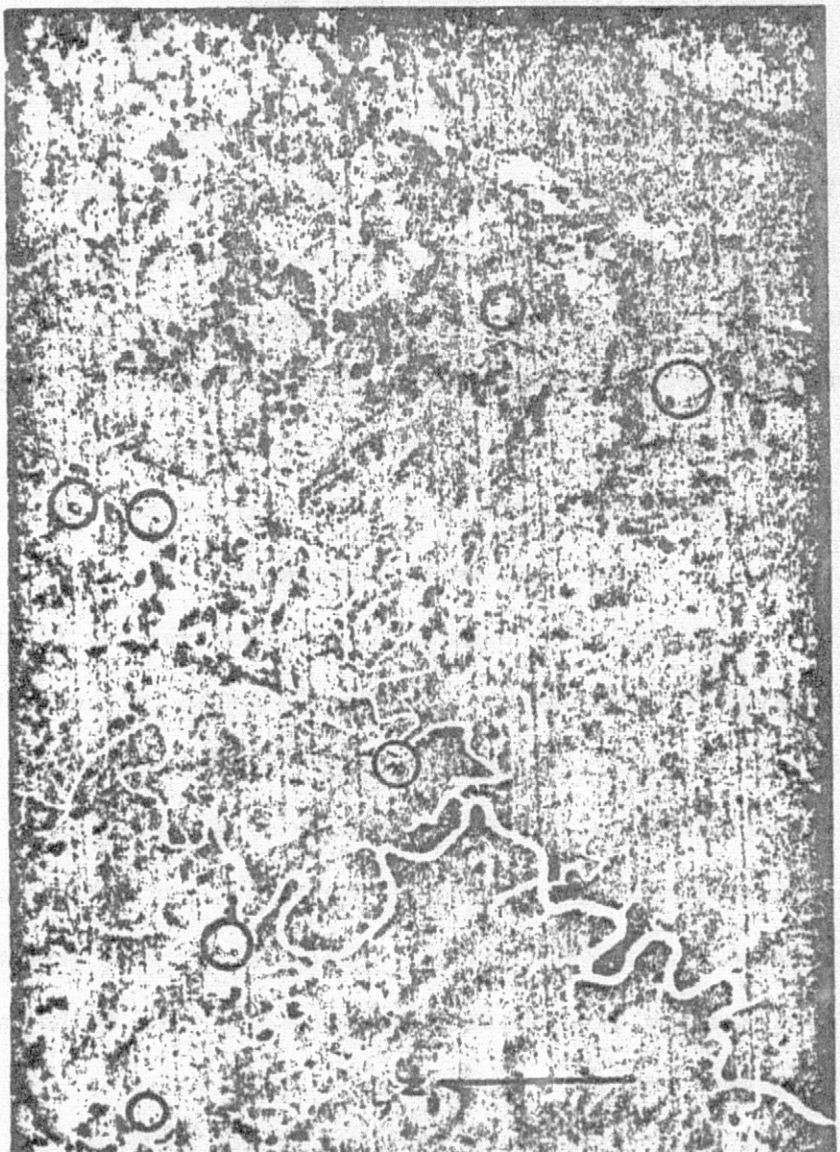

Figure 21. ERTS-I Posoprint of Warrior Basin

applications of ERTS-I imagery is limited because of the small scale of the products. Banding, gray scale stabilization, distortion, and development technique stabilization also present problems of definition and clarity for the ERTS-I data user

4.4 High Altitude Infrared Photography (60,000 Feet)

The high altitude photography used in this study sensed radiation in the red and infrared wave length range of 510-900 nm. The original images were in color; but for purposes of study and reproduction, the photographs used were black and white posoprints. Figure 22 is a black and white photograph enlargement of a color infrared transparency. This image demonstrates many of the inherent characteristics of the coal spoil embankment.

Upon examination of Figure 16, the observer can identify the boundaries of the embankment. The small stream on the western side of the spoil pile is relatively brighter when compared to the bank. The coal settling pond in the eastern cove is also lighter than the dump. The surrounding buildings, vegetation, and fields are readily distinguishable from each other. A color photograph presents excellent color contrast and distinction where the black and white must rely totally on gray scale changes.

As the dump is surveyed for indications of fire, the clay cover (which is reflected nearly black on Figure 22) is readily distinguishable. The primary variable defined in this example is the sensivity of the film to color changes. On the subject photograph, the large erosion patterns on the southwest corner of the dump are also evident. Hot areas and fires were detected on a number of the other embankments

Figure 22. High Altitude Infrared Posoprint-Parrish Dump

studied by these color changes. Most of the fires or hot spots could be termed "old" because of the red oxidized shale ("red dog") left on the surface. The red material differs noticeably from the typically gray-black coal spoil on an infrared photograph of this type.

The high altitude infrared actinic image is useful as a means to detect visible effects and symptoms of a coal spoil embankment fire. However, a fire must be noticeably evident before it is recorded by this system. By that time, the fire would likely be out of control or at least would be very expensive to arrest and extinguish. The primary function of a successful remotely-sensed system should be the early detection of the fire.

4.5 Scanning with the Thermal Hand-held Instrument

The thermal hand-held infrared scanning instrument is capable of detecting temperature differentials as small as $0.2^{\circ}C$ at close range (less than ten feet). However, as distance increases, the minimum temperature differential that the instrument will detect also increases. The image seen on the display is adjusted to an optimum by the contrast and brightness adjustments as shown on the back view of the scanner (Figure 13).

Initial investigations with the hand-held instrument involve scanning the surface and banks of the spoil pile for warm or hot areas. The hand-held scanner readily detects differences in temperature generated by trees, water, sun-warmed banks, and spoil banks. As the western side of the bank was surveyed, wisps of smoke could be seen rising over several hot spots which were immediately detected by the

scanner. The scanner was mounted on a tripod (Figure 23) and adjusted for optimum clarity.

A camera was focused through the eyepiece and several photographs were taken (Figure 24). These images were analyzed for temperature difference on a qualitative basis. The hottest spots appeared in the two light sections near the bottom of the page. Temperature lessens on the outside edges of the hot spots, which is evidenced by the cloudy haze that disintegrates on the outward edges. Each of the white spots represents a temperature difference on the surface of the spoil dump. The hot spots in the subject figure can be termed as "severe" or "very hot." However, no quantitative values can be assigned to light intensities that are recorded on the photograph.

The south bank of the Parrish spoil embankment also contained hot areas but not nearly as hot as the western bank. These areas could more accurately be termed as "warm spots." Several of these spots are displayed in Figure 25. Note their inconsistency and random display patterns, which have been created by air inflow supplying the combustion in the spoil. The top and eastern surfaces of the dump were scanned with the hand-held instrument without detecting combustion. The sun-heated trees were warmer than the northern and eastern sides of the embankment.

The hand-held thermal infrared scanner proved to be effective in detecting warm and hot spots in the Parrish coal spoil embankment. No quantitative temperature differences could be calculated, but the instrument displayed temperature differentials that could be qualitatively evaluated. Its portability was well suited for the spoil pile environment.

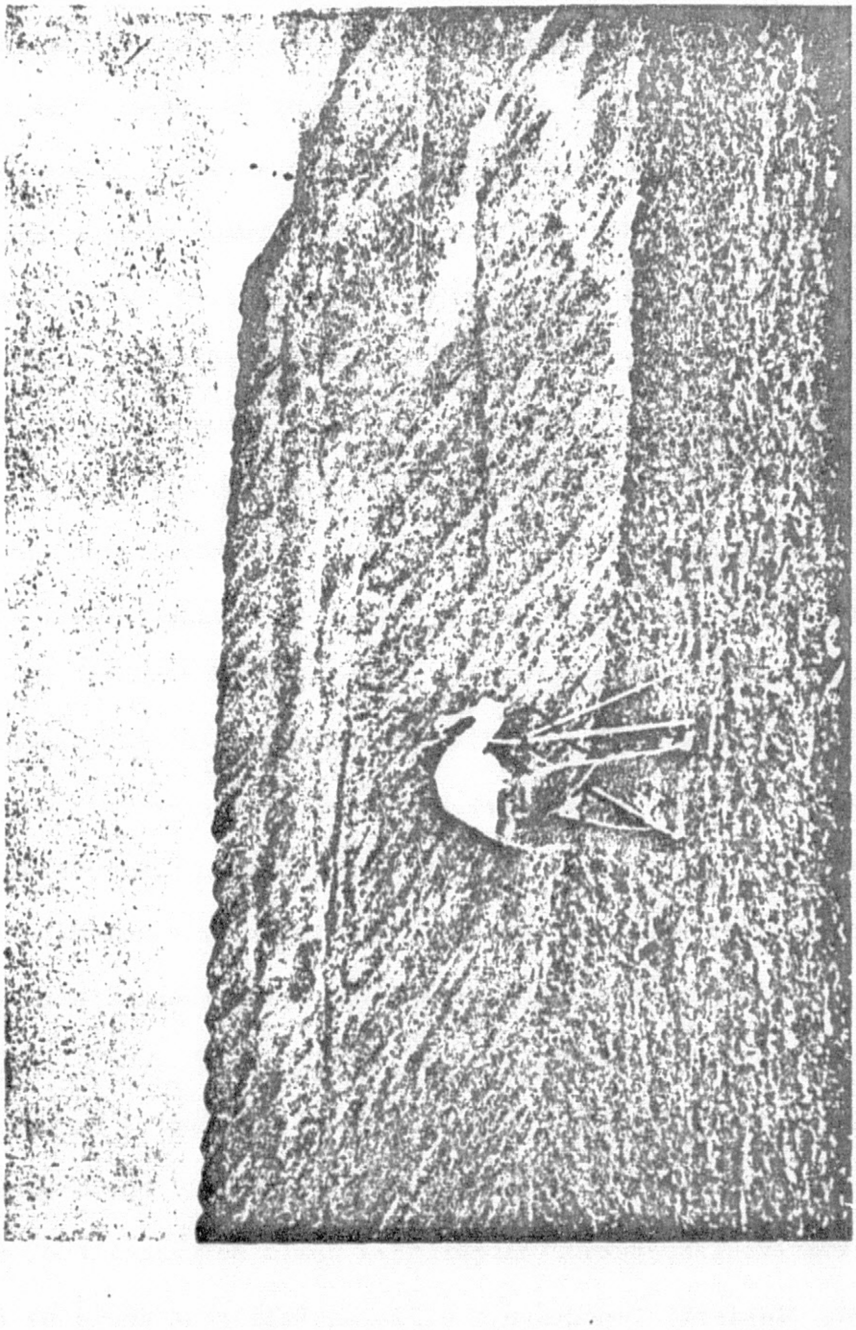

Figure 23. Hand-held Instrument Scanning

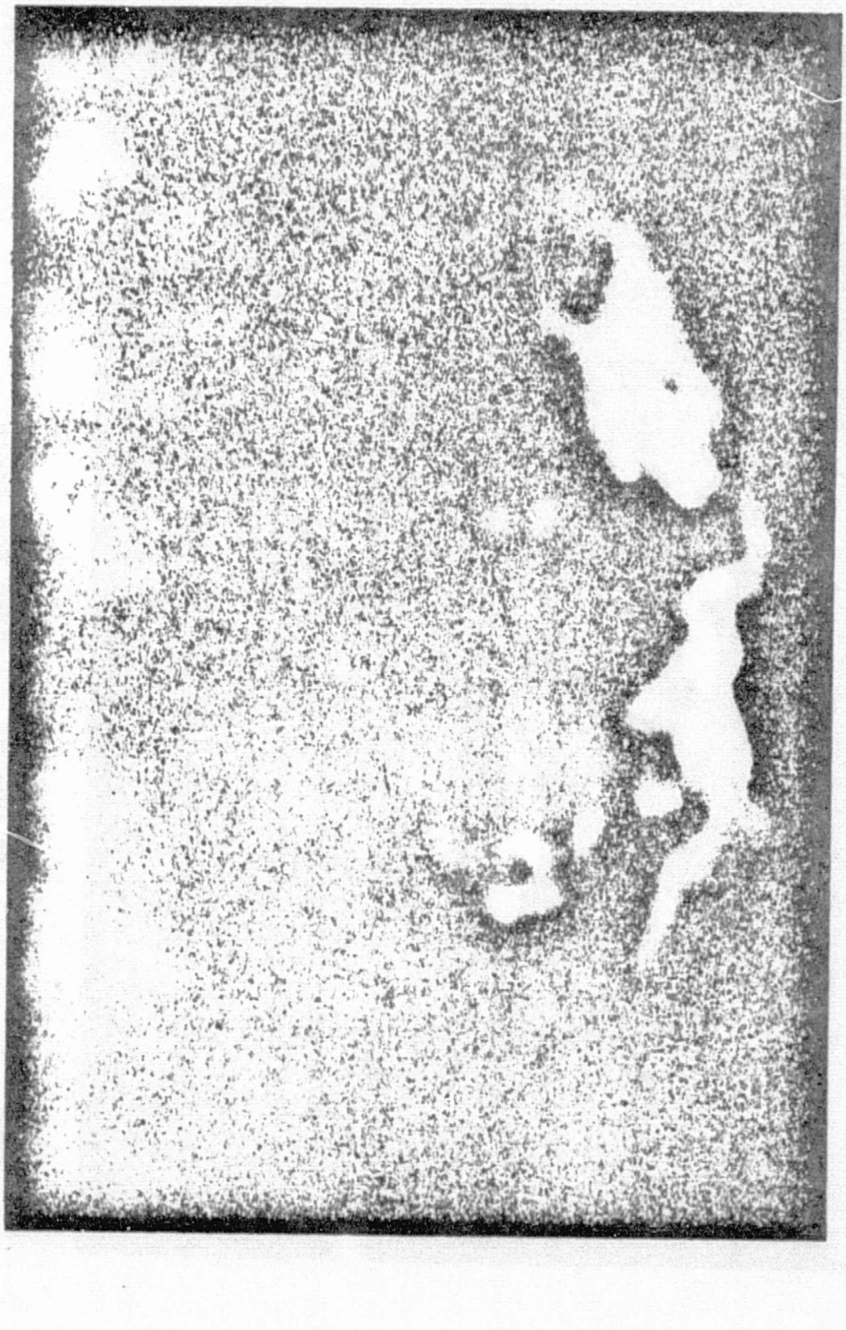

Figure 24. Scanner Image

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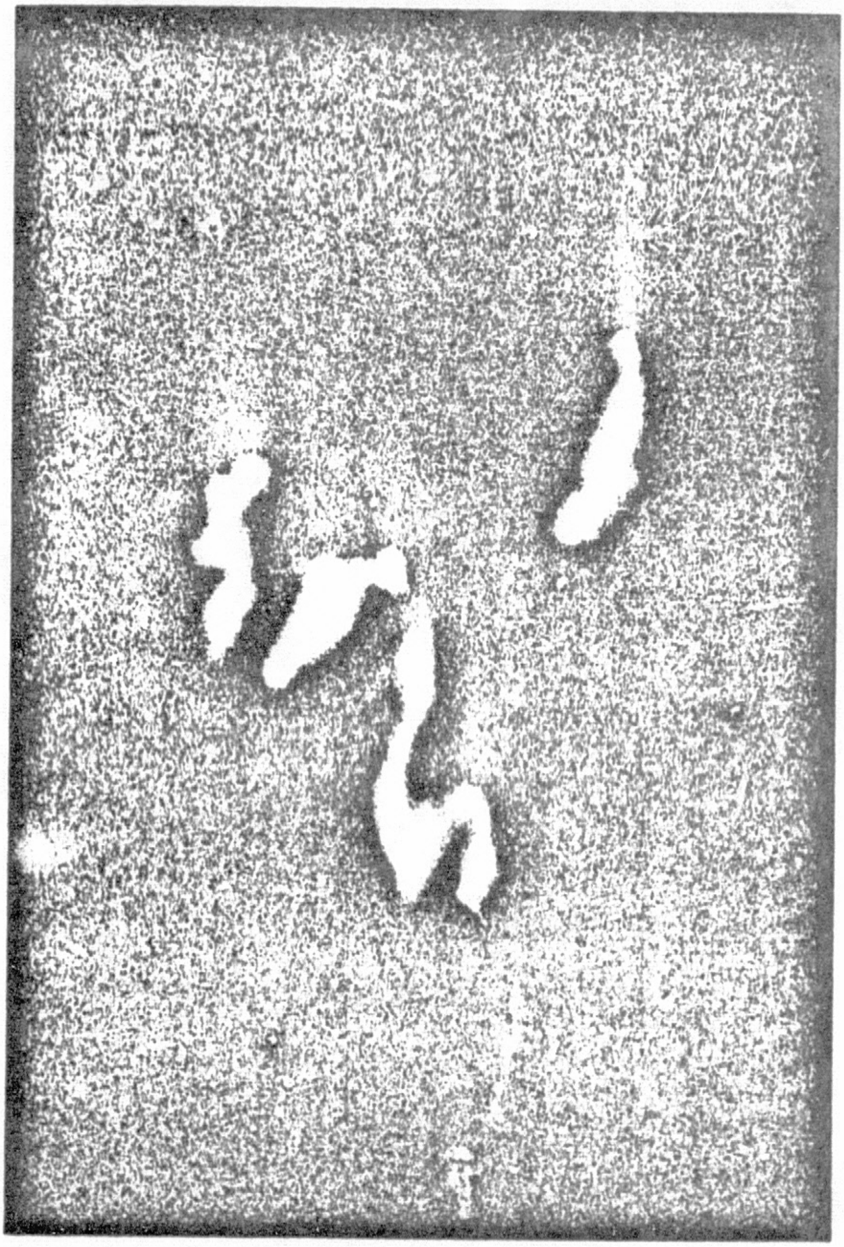

Figure 25. Random Hot Spots

4.6 Imaging with the RS-14 Infrared Instrument

The RS-14 thermal infrared instrument is used primarily on airborne surveys to monitor temperature differences for scientific and environmental purposes. On November 18, 1973, a NASA research aircraft surveyed the major coal spoil embankments in the Warrior Coal Basin with the RS-14 scanner. The weather conditions and flight parameters for the Parrish spoil pile were as follows:

WEATHER - less than 30 percent cloud cover
sunny morning
ground temperature - 75°F
sun angle greater than 30°

FLIGHT PARAMETERS - altitude - 2110.0 feet
heading - 315.7°
drift - 1.6°
roll - 5.9°
pitch - 0.3°
speed - 159.0 knots

A continuous film tape was used to record the image displayed on the cathode ray tube of the RS-14 instrument. From this tape a continuous recording of the scanning was imaged while the RS-14 system was in operation. The result was a black and white negative transparency from which a positive transparency was made. Images of the positive and negative transparencies were developed and are shown in Figure 26 and Figure 27, respectively.

Both images clearly identify areas which have abnormally high temperatures. In Figure 26 the hot areas are indicated by the black

Figure 26. RS-14 Positive Image

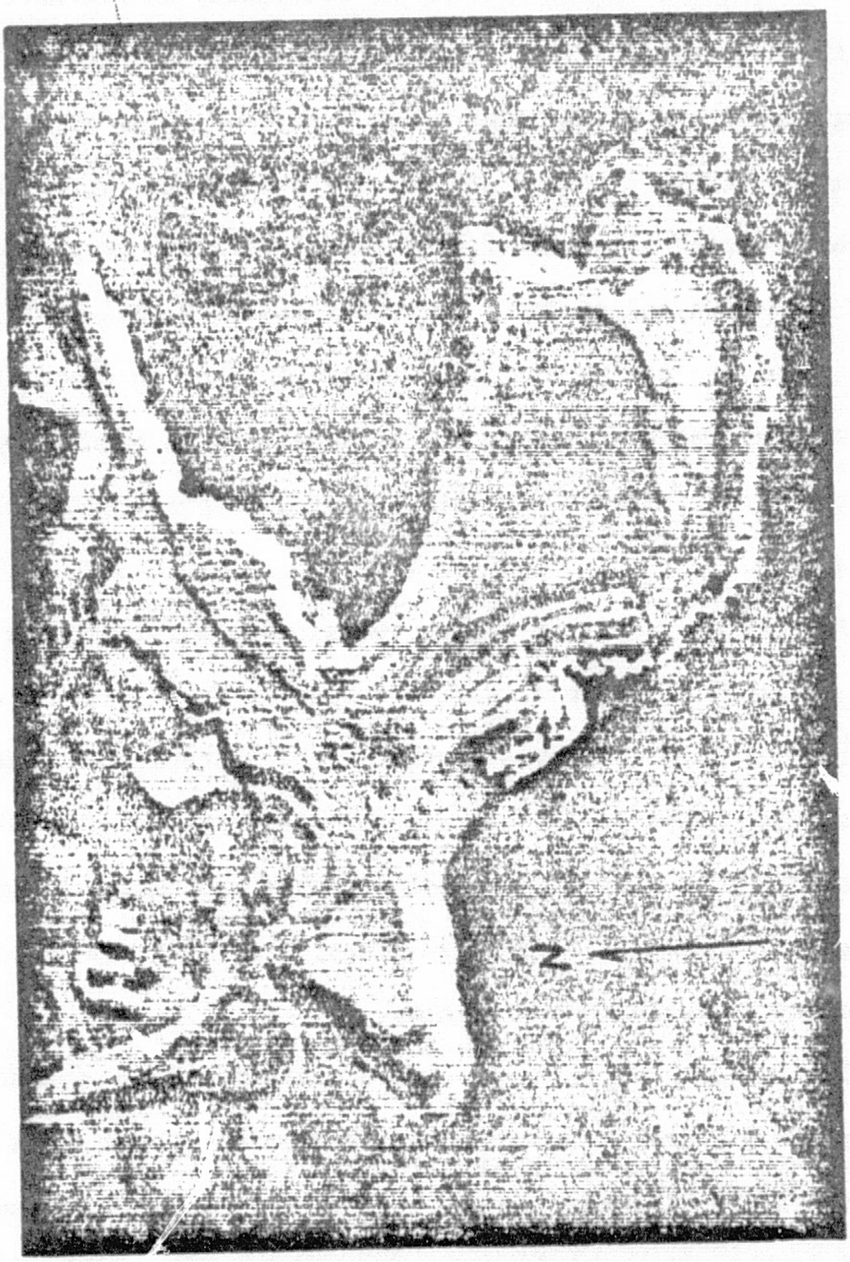

Figure 27. RS-14 Negative Image

areas on the west and south sides of the dump. The temperature is most intense on the western edge of the spoil pile. All of these hot areas were initially delineated by surface observation and with the hand-held scanner, but not nearly as accurately as presented by the RS-14 thermal image. The same can be observed in Figure 27 which is the negative image of the same area. The two images show the same data with reversed colors. The white areas in the latter photograph have the greatest temperature differentials. Both images are useful in the detection and study of these hot areas in coal spoil ambankments. However, the writer feels that the positive image (the greatest temperature differential is indicated in black) appearls more to the eye, because dark shades are more distinguishable than the light shades.

Further study of the images reveals the small details on and around the spoil embankment that are seen on the black and white photograph (Figure 16). The sun is in the southeast as noted by the southeast sides of the terrain being warmer than the other sides. When taken during the day, the image should be checked for variations in temperature created by the sunlight. The ideal time of observation is at night or early in the morning.

The subject images have not been quantitatively evaluated for temperature differentials. However, detection of the spots where the temperature differential was greater than 15-20°C presented no problem to the user. Differences less than approximately 15°C appeared blurred and hazy due to the scanning effect of the RS-14 instrument.

It is possible with special equipment to assign temperatures to the various shades presented on the images. The original temperature image is recorded on magnetic computer tape. A reference black body and white body temperature is recorded by a precision thermometer and supplied to the computer for integration and gray scale identification. The final product can then be analyzed for temperature differences and lines of equal temperatures can be connected to show isothermal areas.

CHAPTER V

SUMMARY AND RECOMMENDATIONS

5.1 Summary

Five remotely-sensed systems which receive electromagnetic radiation were analyzed for their application in the detection of fires and hot spots in coal spoil embankments. Each of the systems received radiation of a different wave length and each was operated at a different distance from the fire areas.

The low altitude black and white photography was useful as a visual aid to identify the various spoil embankments. It was effective as an imaging system in detecting color abnormalities on the embankments. Ordinary photography can be valuable to any user, whether skilled in the remote-sensing field or not. Regular photography was not useful in the detection of warm areas where surface discoloration is not apparent.

The ERTS-I data collection system operates from a satellite and is therefore useful in distinguishing large surface anomalies on the earth. Its accuracy is designed to be 1000 m^2 for the least identifiable object, but actually is much larger. Frequency of sensing is affected by cloud cover, which dictates the data gathering opportunities. In addition, banding distortion, gray scale stabilization, and product development technique stabilization are problems for the ERTS-I data user.

The high altitude infrared actinic photography was useful in the detection of visible effects of coal spoil fires. The altitude of photography was not high enough to destroy the required resolution of an enlarged image. However, the high altitude system was limited by the same features as the low black and white photography. The actinic infrared photography was not useful to detect temperature differences.

The hand-held thermal infrared instrument proved its effectiveness in monitoring temperature differentials on coal spoil embankments. As a portable one-man scanning device, it was practical on location and was easily transported. The instrument was not designed to give quantitative temperature differentials but was accurate in detecting temperature differences of $5^{o}C$ at 100 meters.

The RS-14 thermal infrared imaging system accurately detected temperature differentials on the coal spoil embankments. The sensitivity of the system was sufficient to monitor abnormalities that were not readily distinguished by mining personnel who worked with the embankments. The RS-14 system used by the writer was not adapted to quantitative analysis but such a system is available for industrial use upon special request. The subject system was useful in accurately surveying a large number of coal spoil embankments in a few minutes.

The cost to survey a coal spoil embankment, utilizing both thermal scanning devices discussed in this study, could be as much as \$5,000-\$10,000 including photograph reproduction. However, a practical application of these techniques may be completed with only

the hand-held scanner. The surface of the dump could be scanned for hot spots by ground observation and by aerial inspection from a light aircraft. A camera could be focused through the eyepiece of the portable instrument to record any heat patterns. Cost for such a surveillance system could be as low as $200-$400.

Thirteen coal spoil embankments were surveyed by the writer for possible fires or hot spots. The following spoil piles showed indications of fires and/or hot spots:

1) The Parrish Dump
2. The Graysville #1 Dump
3) The Graysville #2 Dump
4) The Maxine Dump
5) The Pleasant Grove Dump
6) The Johns Dump
7) The West Blocton Dump

All fires were confirmed by ground observation in addition to the RS-14 imagery and the hand-held infrared scanner. The assimilated data for the 13 coal spoil embankments are listed in the Appendix.

5.2 Recommendations

This investigation has created the need for research in the following areas:

1. A comprehensive study in the fields of autogenous heating of coal spoil and heat transfer in spoil embankments.

2. An environmental impact study of a burning coal spoil pile.

3. Applications of computer analysis to quantify gray scale changes on a thermal image.

A P P E N D I X

TABLE 9

FIRE DATA ON SURVEYED EMBANKMENTS

	Name of Dump	Size (Ac.)	Fire Present	Size of Fire (Ac.)	% of Dump on Fire	Fire Location	Remarks
1.	Parrish	12-15	Yes	1.4	11.0	SW edge	Young fire, See Figures 26 and 27
2.	Maxine	14-16	Yes	1.0	6.5	SW edge	See Figure 28
3.	Concord	70-80	No	-	-	-	
4.	Johns	5-7	Yes	0.3	5.0	SW corn.	See Figure 29
5.	Piper	6-8	No	-	-	-	
6.	West Blocton	1-3	Yes	0.1	5.0	SW corn.	See Figure 30
7.	Maylene	8-10	No	-	-		
8.	Graysville #1	2-4	Yes	1.0	30.0	SW side	See Figure 31
9.	Graysville #2	11-14	Yes	3.0	24.0	SW edge	See Figure 32
10.	Graysville #3	9-13	No	-	-	-	
11.	Gorgas	3-5	No	-	-	-	
12.	Pleasant Grove	35-40	Yes	10.0	27.0	SW side	See Figure 33
13.	Mulga	2-4	No	-	-	-	

TABLE 10

ANALYSIS OF B&W, ERTS-I, AND INFRARED COLOR PHOTOGRAPHY

Name of Dump	Black & White Photography				Infrared Color Photography				ERTS-1 Photography			
	Pile Detection	Pile Boundaries	Coloration	Heat Sensing	Pile Detection	Pile Boundaries	Coloration	Heat Sensing	Pile Detection	Pile Boundaries	Coloration	Heat Sensing
Parrish	G	G	G	P	G	G	G	P	G	F	P	P
Maxine	G	G	G	P	G	G	G	P	G	F	P	P
Concord	G	G	G	P	G	G	G	P	G	G	P	P
Johns	G	G	F	P	F	F	F	P	P	P	P	P
Piper	G	G	F	P	F	F	F	P	P	P	P	P
West Blocton	G	F	F	P	F	P	P	P	P	P	P	P
Maylene	G	G	G	P	G	G	G	P	F	F	P	P
Graysville #1	G	F	F	P	F	P	P	P	P	P	P	P
Graysville #2	G	G	G	P	G	G	G	P	G	F	P	P
Graysville #3	G	G	G	P	G	G	G	P	G	F	P	P
Gorgas	G	G	G	P	G	G	G	P	F	P	P	P
Pleasant Grove	G	G	G	P	G	G	G	P	G	G	P	P
Mulga	G	G	G	P	G	G	G	P	F	P	P	P

G - Good
F - Fair
P - Poor

TABLE 11

ANALYSIS OF HAND-HELD AND RS-14 SCANNERS

	Hand-Held Scanner				RS-14 Scanner			
	Pile Detection	Pile Boundaries	Coloration	Heat Sensing	Pile Detection	Pile Boundaries	Coloration	Heat Sensing
1. Parrish	N/A	F	P	G	G	F	P	G
2. Maxine	N/A	F	P	G	G	F	P	G
3. Concord	N/A	F	P	G	G	F	P	G
4. Johns	N/A	F	P	G	F	F	P	G
5. Piper	N/A	F	P	G	F	P	P	G
6. West Blocton	N/A	F	P	G	F	P	P	G
7. Maylene	N/A	F	P	G	G	F	P	G
8. Graysville #1	N/A	F	P	G	F	P	P	G
9. Graysville #2	N/A	F	P	G	G	F	P	G
10. Graysville #3	N/A	F	P	G	G	F	P	G
11. Gorgas	N/A	F	P	G	G	F	P	G
12. Pleasant Grove	N/A	F	P	G	X	X	X	X
13. Mulga	N/A	F	P	G	G	F	P	G

N/A - not applicable
X - mechanical problem
G - Good
F - Fair
P - Poor

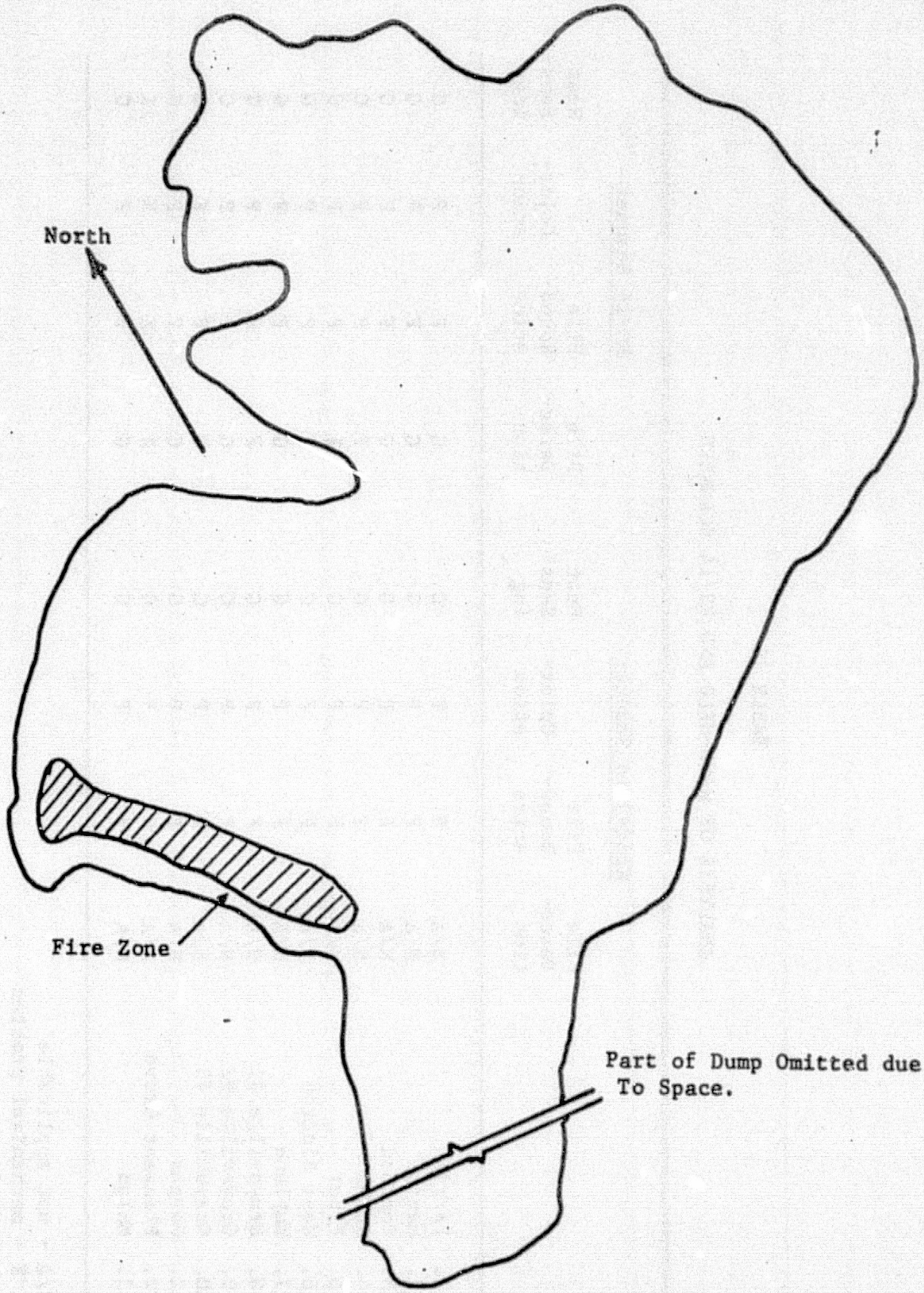

Figure 28. Outline of the Maxine Dump

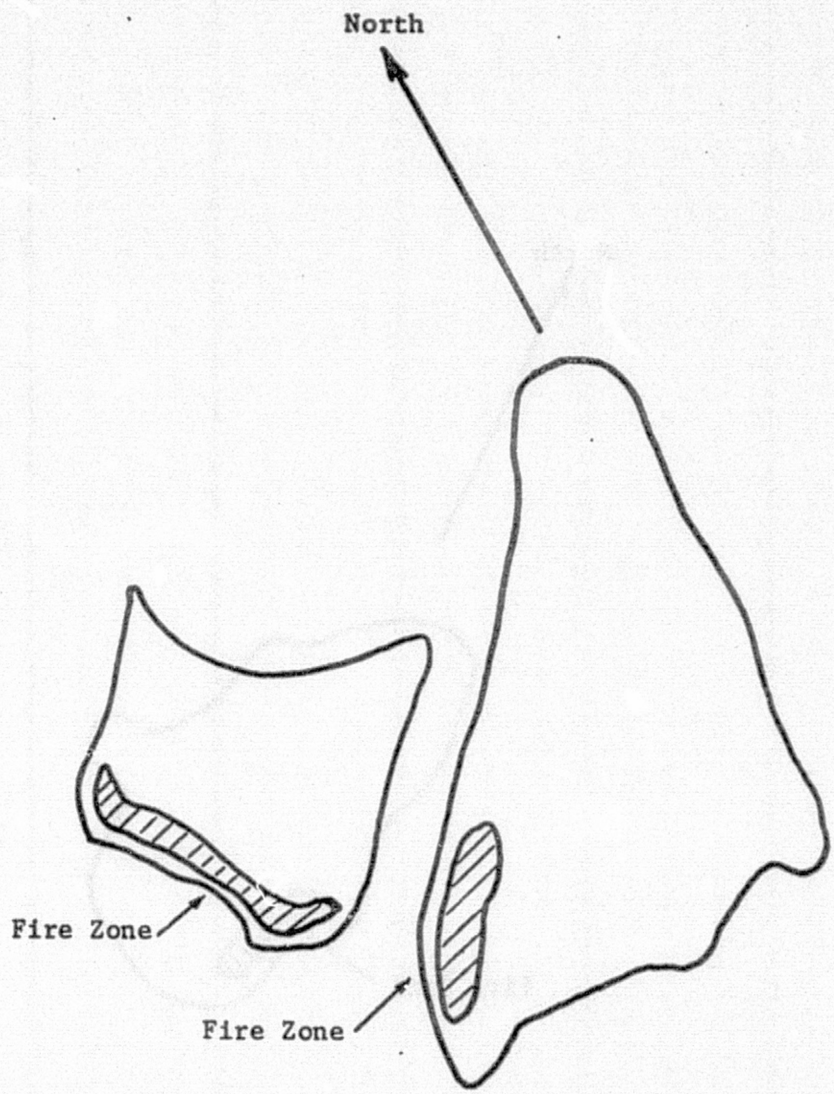

Figure 29. Outline of the Johns Dump

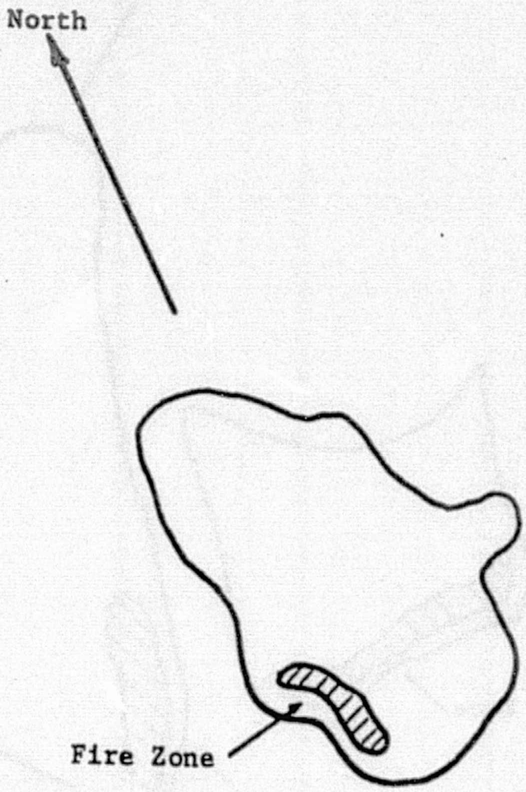

Figure 30. Outline of the West Blocton Dump

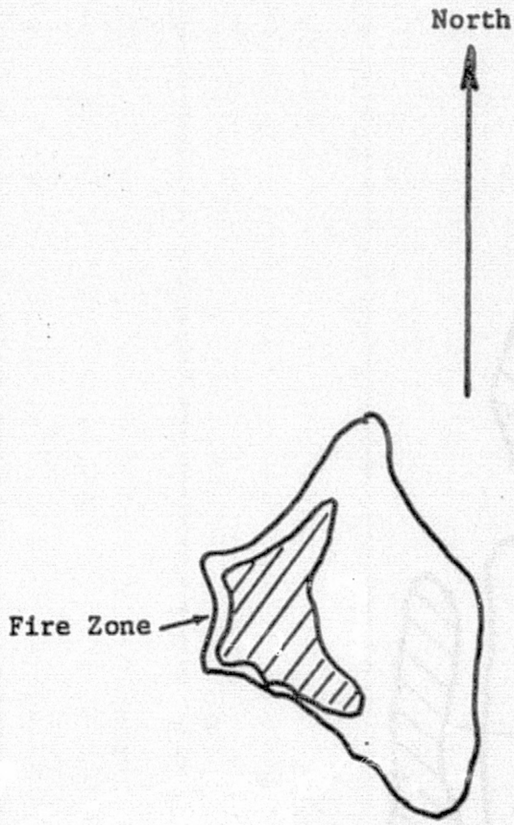

Figure 31. Outline of the Graysville #1 Dump

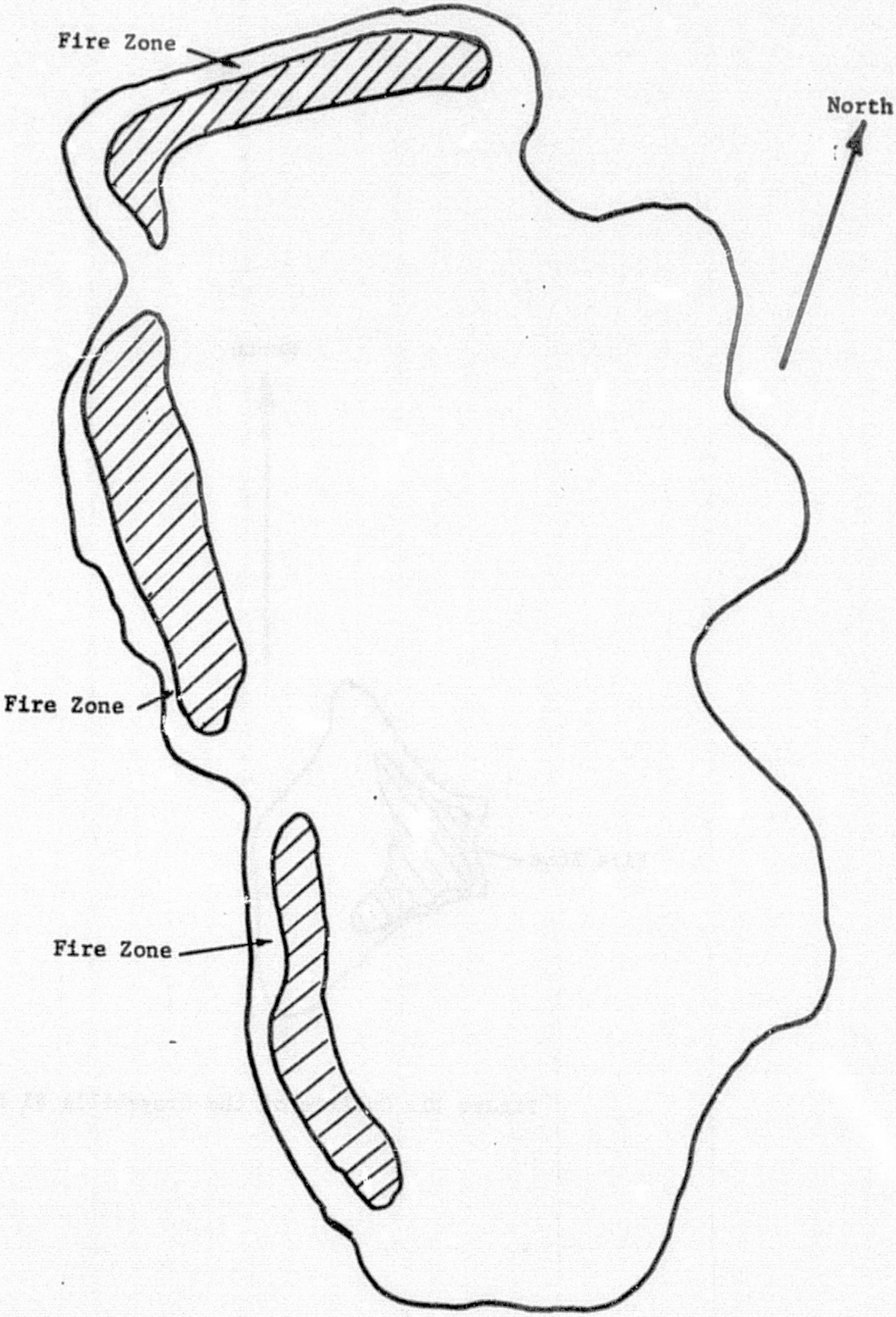

Figure 32. Outline of the Graysville #2 Dump

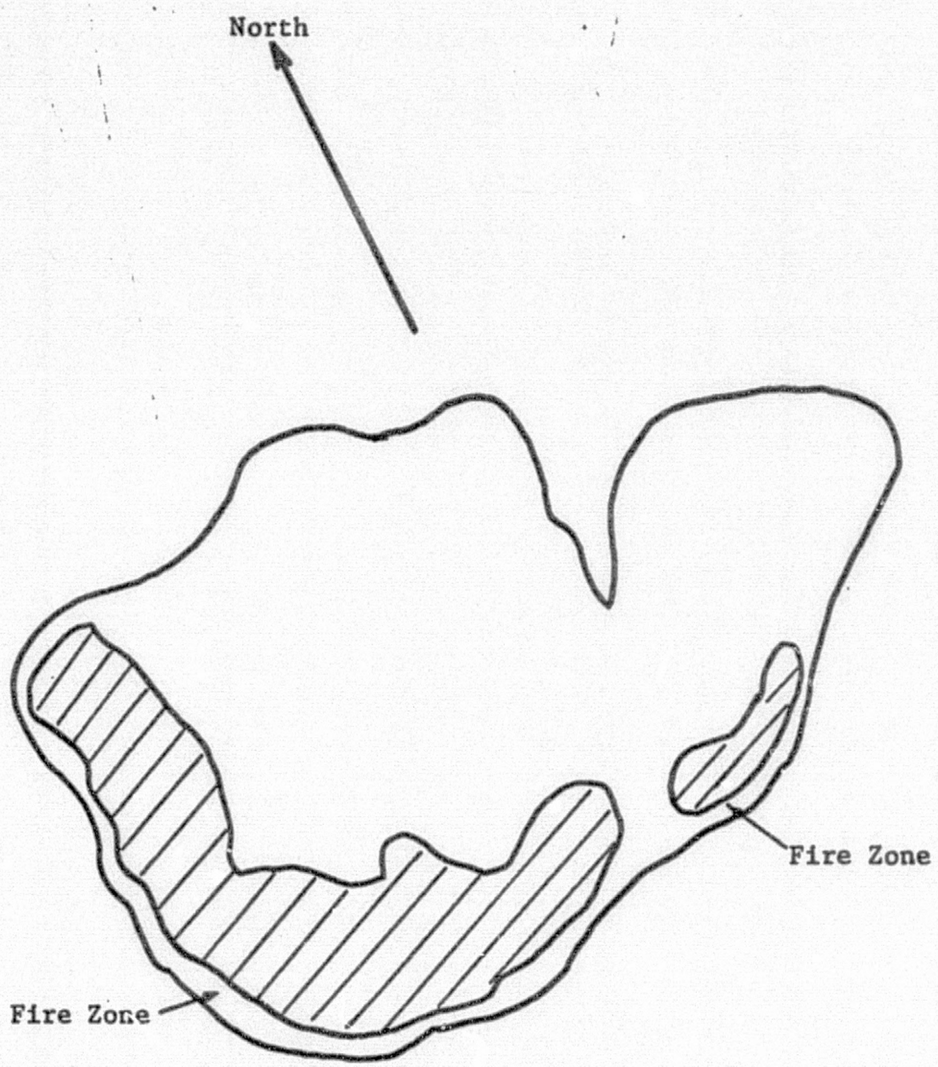

Figure 33. Reduced Outline of the Pleasant Grove Dump

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REPORT OF PROGRESS OF CLUSTERING TECHNIQUE

Sam A. Schillaci

SECTION ELEVEN

of

VOLUME TWO

INVESTIGATIONS USING DATA IN

ALABAMA FROM ERTS-A

REPORT ON PROGRESS OF CLUSTERING TECHNIQUE

S. A. Schillaci

In our work of interpretating some form of raw data into a manageable land use information file, the University of Alabama's ERTS project had focused most of its attention of acquiring land use information manually from some sort of visual representation such as an ERTS or an aerial photograph. There were no attempts to interpret the data by some other means such as supervised or unsupervised techniques. Recently, some work has been done in developing a clustering method, called the Modal Search Technique (MST), and its application of this method as an unsupervised interpretation technique for multispectral scanner data. A computer algorithm has been developed and tested with good results, but it is too unfortunate that the method was developed so late in the term of the ERTS research contract.

There were four points considered in the development of the clustering algorithm concerning large clustering problems. Any algorithm must consider these points regarding limitations of core storage and CPU time in solving large problems such as the ERTS MSS data:

1. Repetition of the data
2. Speed of the clustering measurement
3. Generality of the shapes and distributions of the computed clusters
4. Applying the generated labels to the raw data

The amount of repetition is usually very high with large amounts of data. The data values around a distribution's mean occurs many times, especially if the values are integer. If an algorithm has to apply its

measure to each repetitious value, the time or storage will most likely be affected.

The next point an investigator must consider in designing an algorithm is the measurement used. A complicated measure may work well with a few data points with no significant differences than any other measure, however, when applied to 10,000 or more values, the time to compute the measure may be exorbitant.

As in figure 1, much of the displayed clusters do not follow any particular pattern. An algorithm that can handle only multi-dimensional data that is hypercircular or hyperelliptical will not be able to classify data with any other shape without an intolerable rate of misclassification.

The last point may be an important factor to consider where actual relabeling the data to its new cluster values is important. For example, with the ERTS data it may not be sufficient to discover the clusters, but this information should be used to draw maps showing the relation of the derived class with its actual physical ground location. Thus a fast method of relabeling the points must be implemented.

With the techniques presented, two types of relabeling exist: parametric and lists. The distance from the raw data point to the set of parameters (mean value) of each class has to be computed to see if the point lies within the class boundary. This type of process may take as long as the actual clustering process. The second relabeling method is to search the generated sets or class lists until the point to be classified is found. This also is time consuming unless the set of clustered data points are arranged in an easy to locate manner. The large amounts of storage needed is the main handicap of this type of relabeling.

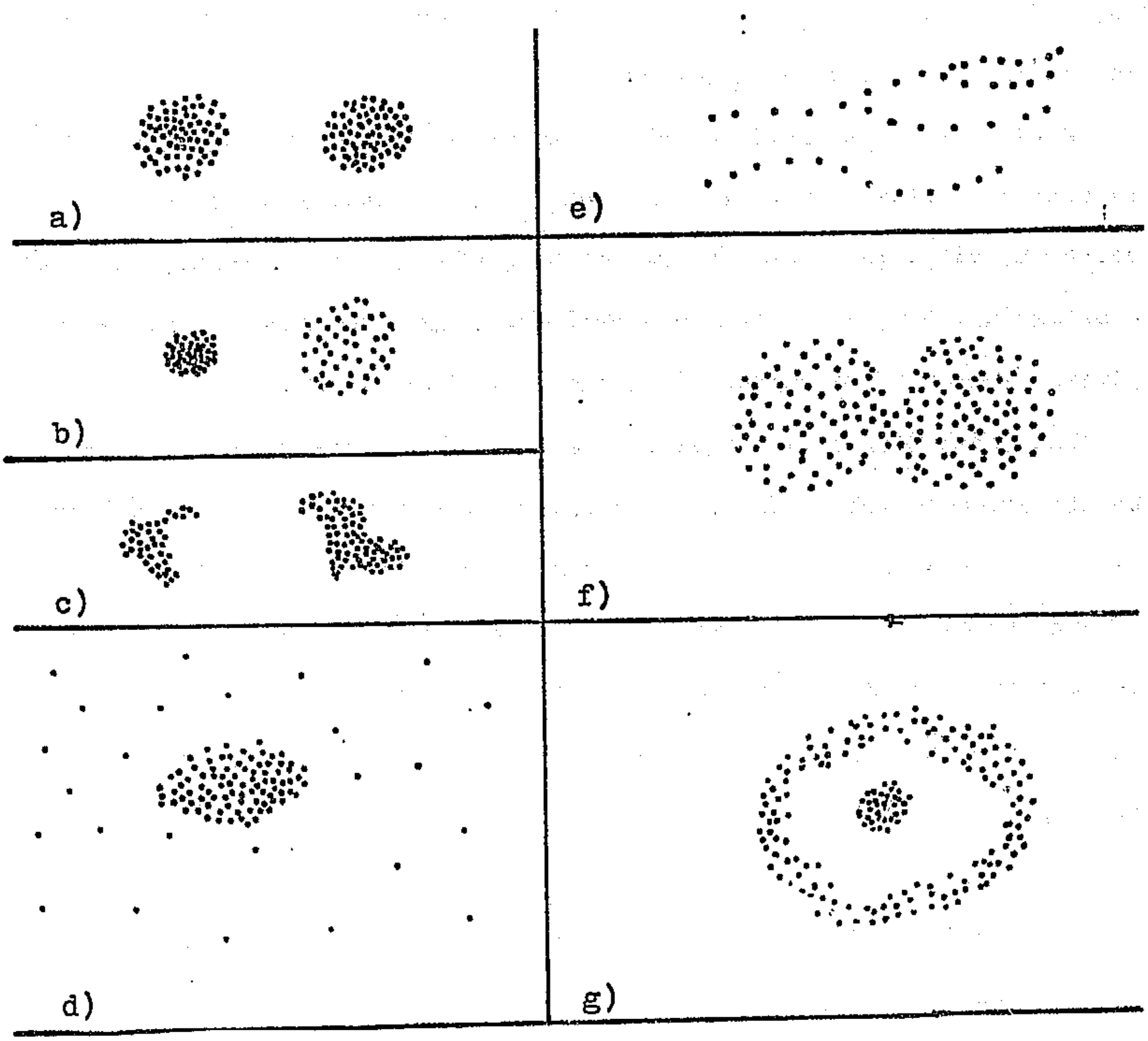

Figure 1. Some Typical 2-Dimensional Cluster Problems

a) Equal density clusters
b) Unequal density
c) Concave clusters
d) Cluster with noise
e) Linear cluster
f) Touching clusters
g) Cluster within a cluster

The Basic MST Clustering Algorithm

With some "real world" problems, an exact or elegant approach may not be very economical. Certain shortcuts must be applied to reach a good solution, although it may or may not be optional. An approach, heuristic programming, may be a better means of arriving at an answer given a limited amount of resources allocated to problem solving.

The modal search technique is heuristic in nature, with the four points given in mind. The basic solution technique is centered around two arrays (which is combined into one in the complete algorithm): a cluster array and a count array. One important fact about these arrays is that the position in the array determines the value of the data point. This eliminates the repetition factor since two data points that have the same values share the same position in the arrays and a third point, that has a different value does not occupy the same position. The count array holds the number of occurrences for each point; the cluster array tells which class the point was computed to belong to.

Since the array process is used in the algorithm, the computer model requires all the data values to be integer. Further study had been nade in the area of noninteger values and the use of scaling to help solve this problem.

The measure used in this algorithm is similar to a probability measure. The number of occurrences, given in the count array, determines the relative importance of each data point. Also, another prerequisite of the data is that it is dense within the clusters (which is usually true with large data sets). What this means is that if a data point in the count array has a number of occurrences, then the probability that a close or adjacent point having at least one occurrence is large.

A neighborhood measure is also applied in this algorithm. This measure uses the concept of an adjacent point. In vector terms:

A vector $Y = (y_1, y_2, \ldots, y_L)$ is adjacent to the vector

$$X = (x_1, x_2, \ldots, x_L) \text{ iff}$$

$$|x_i - y_i| \leq 1; \quad i=1,2, \ldots, L$$

The actual neighborhood is defined as all adjacent points--including the given point. This type of neighborhood measure was used because of its speed of computation and, with other neighborhood measures, ability to detect complex clusters.

The variable Z is used as a counter to tell how many different clusters have been distinguished. The steps in the procedure are:

1) Initialize count array, cluster array, and Z to zero.

2) Input all the data points and count into its proper position in the count array.

3) Find the largest count > 0; If all are ≤ 0 then go to step 8.

4) Find all the neighboring points and count the number of each that are classified in the cluster array.

5) Any neighbors classified? If no assume a local maximum and go to step 7, else continue.

6) Classify all neighbors (including point found in step 3) into the predominate class, change values in count array to minus, go to step 3.

7) Local Max: If any neighbors have the same value as the largest count, signify this and go back to 3 (set value to -99). Else classify all neighbors as the class Z+1, change values in count array to minus, go to step 3.

8) Go back over count array and try to classify any points that were left unclassified (from step 7).

9) Pass through original data set and relabel each point from the cluster array.

Testing of the Complete Algorithm

Two cases were studied using the MST algorithm with a few changes made

in the basic model. The Fisher Iris data and two sample areas were analyzed by the technique.

The Fisher Iris data is a classical data set used by many clustering investigators for testing. The data set contains measurements on three species of Iris. A total of 150 flowers, 50 from each group, were given; the measurements being: petal length, petal width, sepal length and sepal width.

A number of tests were performed by varying the size of the arrays. Each run divided the data into three classes. An error term was computed to rate the classification ability of each run. It was defined as:

$$\text{ERROR} = \frac{\text{NUMBER MISCLASSIFIED}}{\text{N}}$$

N = Total number of data points

The errors for the Iris data ranged from a low of 8 percent to 14 percent; or 12 to 21 misclassified out of 150. The average CPU time to classify the data on a RCA Spectra 70/6 was 20 seconds. Another clustering program, called the Ward's hierarchical clustering method grouped the data into three classes with an 11 percent error in 1 minute, 30 seconds CPU time.

Two study areas in the vicinity of Tuscaloosa, Alabama were the next test for the algorithm. These two areas had been classified before by another clustering technique, called the Composite Sequential Clustering (CSC) technique, using ERTS MSS data. Also the areas had been classified manually from aerial photography.

Study area one, or the stripped area, is in west-central Tuscaloosa County. It is an isolated area consisting mainly of strip mines and forests. A portion of the Black Warrior River runs through the center of

it. Although the area contains very few types of land uses, the ERTS data contained clouds and cloud shadows. This is usually very detrimental to many interpretation techniques causing much misclassification and unclassified samples because of the highly varied statistics. This was noted in a map of the classifications from the CSC method.

The MST method classified the area into seven classes. A map of the classes in the area was printed and colorcoded by hand. From this map, a visual analysis corresponded the following classes with the ground truth. Class 1 corresponded visually to forest areas or areas with trees. Class 2 traced out the Black Warrior river so it was assumed to be the water class. However, some cases of it were scattered around cloud shadows. Class 3 had spectral values close of that to class 2, but it was concentrated at areas of cloud shadows. Class 4 occured in areas of strip mines but also was found in the fringes of clouds. Classes 5, 6, and 7 were high spectral readings and corresponded to clouds.

Using these classes as an indicator for the land use, a test was run against a manual analysis of the same area. Using the error term given above, an error of 27 percent was calculated, at 73 percent accuracy. The CSC method scored a 55 percent accuracy of on the same area.

The second area, southwest Lake Tuscaloosa, contained a larger variety of land uses. Figure 2 is the MST classification of the area printed in a character map form. The samples printed with slashes (/), was class 3 and corresponded with the water in the area. The section in the upper right hand corner corresponded to a section of the impounded Lake Tuscaloosa, and the stream of slashes in the bottom of the figure matched with the Black Warrior river. Class 1 or the periods (.) matched in many cases with areas of forest. Class 2--the dashes (-)--matched to the large areas of

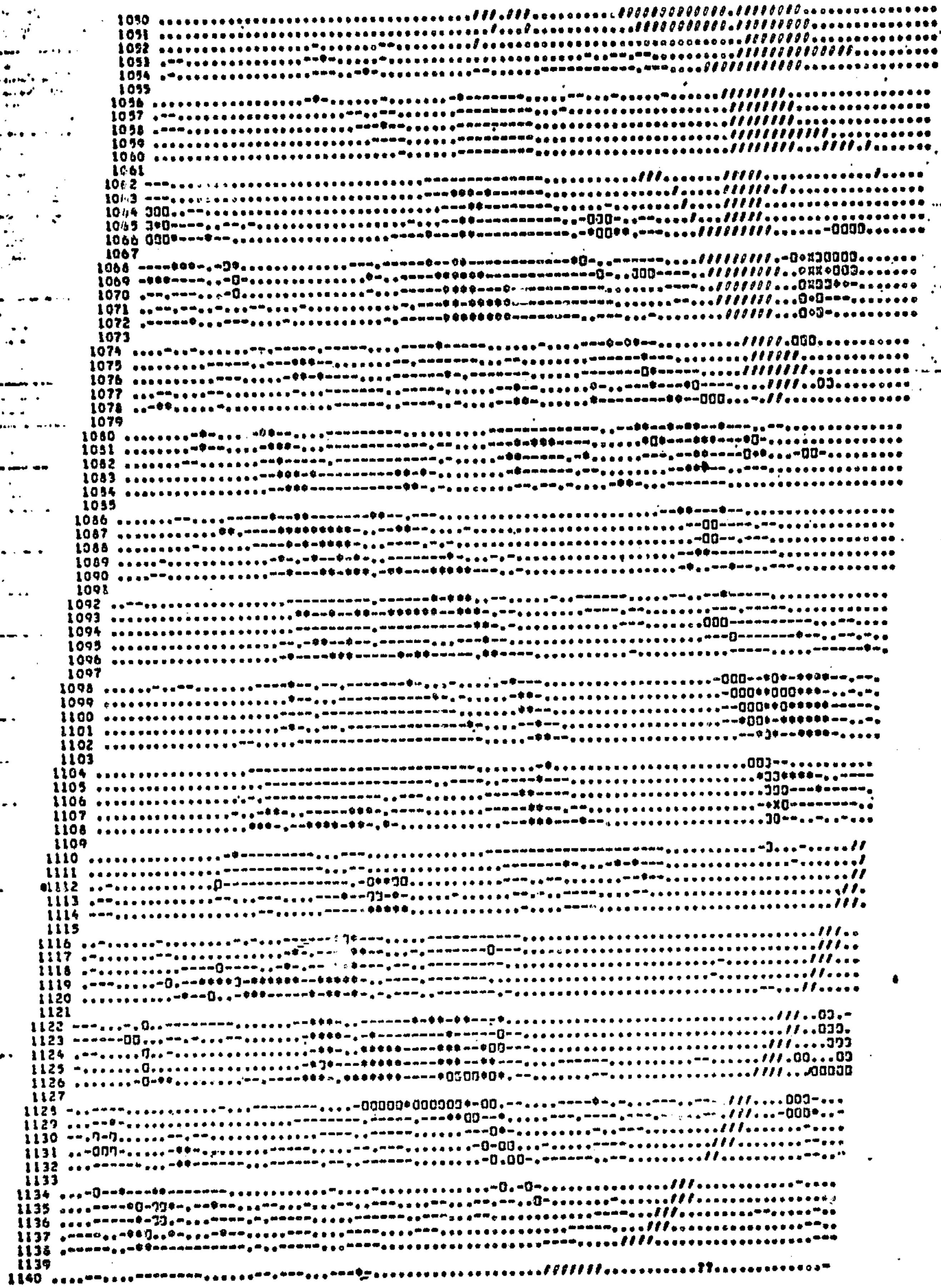

Figure 2. MST Analysis of Study Area Two

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agriculture, grass, and pasture areas; however, class 4 (*) seemed to follow these areas, with more congregation around tilled soil and residential areas. The areas printed with O's, X's and +'s indicated areas of barren and built up lands.

An accuracy study is not yet completed at this time. The analysis by the CSC technique on the area performed relatively well, however much of the area was left unclassified. Two samples were left unclassified by the modal search method.

In terms of cost of such a study for land use interpretation, some analysis has been completed. The results (Table 1) were run on 4 test areas; the two introduced and two other test areas called T1 and T2. Area T1 was an area with the same number of samples as study area two but not as complex. Area T2 was a large area, used to test how the method works with many samples. In both areas the accuracies seemed comparable to the first study areas, although no in depth studies were performed.

The costs figures were arrived by assuming a rate of $200 per hour on the Spectra 70/6 running in an emulator mode to replace an IBM 360-50. The larger an area is classified at a time, the less expensive it is per kilometer to analyze the total area. Also the cluster and map time is decreased if the area is less complex with fewer classes. Overall, on a regional basis, using the MST to classify large areas, the cost figures would be more like the ones for area T2 or about 9¢ per kilometer computer cost. On a more specialized basis the costs increase.

The complete results of this research and an explanation of the mathematical models used in the modal search technique is planned to be reported in a Master's thesis, to be released sometime in the near future.

TABLE 1

MST COST STUDY

Study Area	# Samples	# km*	# Classes	Copy Time (sec) Total	Copy Time (sec) Per km	Cluster Time (sec) Total	Cluster Time (sec) Per km	Map Time (sec) Total	Map Time (sec) Per km	Cost (cents) Per km
1	9780	42.48	7	14.62	0.34	52.10	1.23	57.64	1.36	0.163
2	6916	30.04	9	12.92	0.43	53.15	1.77	36.24	1.2	0.189
T1	6916	30.04	5	13.51	0.45	48.11	1.60	34.01	1.13	0.177
T2	30394	132.02	7	43.12	0.33	64.43	0.49	106.65	0.81	0.091
T3	61305	266.28	6	35.07	0.13	99.14	0.37	170.76	0.64	0.063

* 230.23 samples/km